LIFE CYCLE EVALUATION OF

CO_2 RECOVERY AND SEQUESTRATION SYSTEMS

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Without their sharing of knowledge and feedbacks, the research work would not have been successfully carried out to its present magnitude and height.

DEDICATION

To GOD

May your children grow in higher wisdom and knowledge

And learn to cherish the Earth

That You have so lovingly created

With greater sincerity and devotion

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SUMMARY

Rising levels of carbon dioxide (CO_2) in the atmosphere have been linked to possible irreversible changes to the earth's climate. For the past few years, many types of CO_2 fixation technologies are being investigated to reduce the amount of CO_2 that is accumulating in the earth's atmosphere.

The author sets forth to investigate three linked stages associated with the amount of, as well as, methods of reducing atmospheric CO_2. First, the pollutants and by-products associated with coal mining, transportation and coal-fired power generation were identified with and compiled. Next, in order to reduce the amount of CO_2 generated for every MWh of electricity generated from the power plant, CO_2 capture or recovery technologies must be installed. In the second stage, four types of CO_2 recovery technologies were considered: chemical absorption, membrane separation, cryogenic fractionation and pressure swing adsorption. These technologies were assessed according to the amount of CO_2 successfully recovered from the power plant's flue gas along with their associated energy requirements.

Stage three looks at various CO_2 sequestration options – ocean, geological and mineral. For ocean sequestration, five case studies are presented: Vertical Injection, Inclined Pipeline, Pipe Towed by Ship, Dry Ice and Gas-lift Advanced Dissolution or GLAD system. For the next option, the potential storage of CO_2 in geological formations is studied alongside enhanced oil and natural gas recovery applications. In the third and final option, mineral sequestration, five routes for CO_2 carbonation is analyzed.

Life Cycle Assessment (LCA) was used throughout the project as a scientific tool to evaluate each of the CO_2 recovery or sequestration processes proposed in the advent of preventing global warming. LCA is applied to evaluate the CO_2 mitigation systems based on their potential to reduce the final amount of CO_2 in the atmosphere (i.e., prevention of global warming), against their accumulated release of other types of pollution (air and water emissions, toxic gases, wastes, etc) due to the energy requirements of each process involved. In this manner LCA is used to provide a systems-wide approach for looking at every option, and to ensure that the very action taken for reducing the amount of CO_2 does not itself create other (bigger) types of environmental burdens.

The EDIP (Environmental Design of Industrial Products) method was applied to generate the impact assessment results of the CO_2 recovery and sequestration methods – first as individual (isolated) systems, and next as a continuous chain of processes. Eight environmental impact categories were evaluated: i) Global Warming Potential, ii) Acidification, iii) Human Toxicity to Air, iv) Human Toxicity to Water, v) Eutrophication, vi) Ecotoxicity, vii) Wastes and viii) Resources.

The EDIP was also used to generate the Final Weighted scores of all the combinations of the CO_2 mitigation systems. Next, Sensitivity Analysis was carried out for comparing: i) lower and higher limits of CO_2 recovery efficiencies, ii) different levels of power plant CO_2 emissions (950, 970 and 990 kg CO_2 per MWh), iii) different Weights used for the EDIP (“Low”, “Med”, “High”), and iv) the final scores generated for the complete system by the EDIP and Eco-indicator.

It was concluded that out of all 12 sequestration options, the two geological methods – EOR and ECBM – offered the most promising approach to sequester large amounts of CO_2, while at the same time, providing additional advantages of resource recovery. This claim was further verified by a hypothesis t-test to be '*extremely significant'*. As for ocean sequestration, the three most feasible options turned out to be Vertical Injection, Inclined Pipeline and Dry Ice – when all three are combined with chemical absorption technology for CO_2 removal.

Mineral sequestration systems were still at the early development stages and further investigations for energy efficient carbonation processes is being required. Out of the five process routes, the most practical solution at present (least energy demands) was by the use of wollastonite.

The different levels of CO_2 emissions (950, 970, 990 kg) from the power plant hardly had any impact on the Final Scores. However, fluctuations of 16% up to 55% in Final Scores were realized throughout with changes in Low, Medium, and High Weights. Hardly any difference in results were noticed when the weights for Human Toxicity (alone) was set to "high", and an average of 50%-60% reductions all round in Final Scores were observed when the weights for GWP (alone) was set to "high".

The EDIP (mid-point LCIA method) and Eco-indicator (end-point LCIA method) both generated impact assessment results which displayed similar trends. The Sequestration Effectiveness results were: 77-92% (ECBM), 73-87% (EOR), 70-87% (Vertical Injection), 68-86% (Dry Ice), 63-78% (Inclined Pipeline), 59-72% (GLAD) and finally, 57-71% (Pipe Towed by Ship).

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LIST OF ABBREVIATIONS

LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
EDIP	Environment Design of Industrial Products
ECBM	Enhanced Coalbed Methane
EOR	Enhanced Oil Recovery
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
GLAD	Gas Lift Advanced Dissolution
GWP	Global Warming Potential
SETAC	Society of Environmental Toxicology and Chemistry
PSA	Pressure Swing Adsorption
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency

CHAPTER 1

Introduction

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Introduction

1.1 Background

Rising levels of carbon dioxide (CO_2) in the atmosphere have been linked to possible irreversible changes to the earth's climate. CO_2 levels are now measured to be 381 *ppm* (parts per million), that is, 100 *ppm* above pre-industrial level (Kerr, 2006; Shukman, 2006). This increase has spurred worldwide concerns of potential global climate change among international organizations, governments and environmental scientists. For the past few years, various projects, research schemes and discussions have been carried out to limit the amount of CO_2 and other greenhouse gases that are released to the atmosphere (Khoo and Tan, 2006a; 2006b; Dijkstra and Jansen, 2004; Herzog et al., 2001).

Global warming or climate change is mainly caused by the burning of fossil fuels to meet worldwide energy demands. In the U.S. alone, over 1.6 Gt (billion tons) of CO_2 is produced each year from power plants (Herzog, 1996). The World Energy Outlook has projected that given the present trend in industrial development, worldwide energy use will grow by 1.7% annually from 2004 until the year 2030, which is an overwhelming 58% increase (World Energy Outlook, 2004).

Many types of methods are currently being investigated to reduce the amount of CO_2 escaping from the power plant's flue gas into the atmosphere. Among those discussed here are post combustion capture technologies, and various CO_2 sequestration

methods (Herzog, 2001; Holloway, 1997). Throughout the report, coal-based electricity is selected as the prime energy provider for the various technologies and systems contained in the report.

1.2 Project Motivation: Rising CO_2 levels and Global Warming

1.2.1 Energy Use and Fossil Fuels

According to Yegulalp et al. (2001), 50% of the increase in CO_2 levels experienced during the past 40 years is mainly caused by human activities. The rapid pace of economic and industrial development worldwide is accompanied by a steady increase in energy consumption (see Figure 1.1).

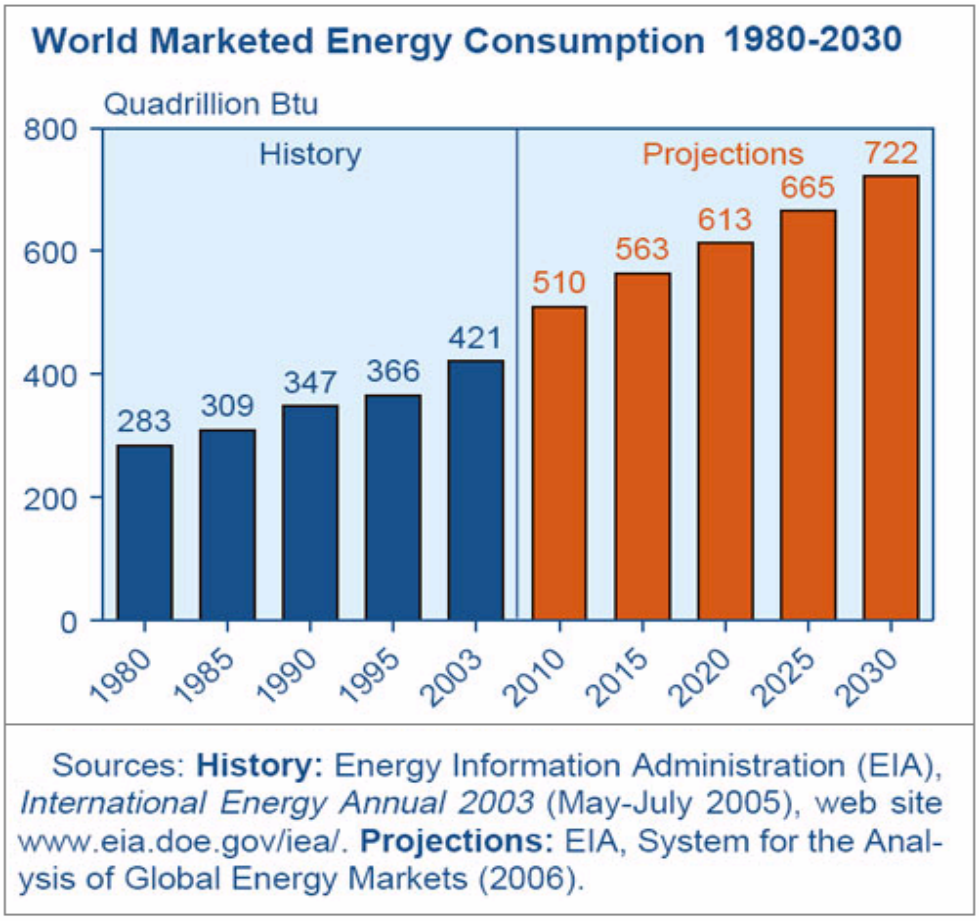

Figure 1.1. Global Energy Consumption: History and Future Projection

The world's net electricity consumption is expected to nearly double over the next two decades, according to the *Energy Information Administration* (EIA, 2006).

At present, 85% of world electricity is generated by fossil fuel, and it has been anticipated that this trend is likely to continue (World Energy Outlook, 2004). Fossil fuels come in three major forms – coal, oil and natural gas. During the combustion of fossil fuels, various types of air pollutions are generated. These air pollutions, which are the most important concerns related to electricity generation, can cause serious damages to the environment. Stack gases from power plants containing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NOx) are known to be responsible for acid rain. Uncontrolled amounts of heavy metal emissions are also known to be harmful to human health. Finally, greenhouse gases such as CO_2, nitrous oxide (N_2O) and methane (CH_4), which have become the world's major environmental concern, are classified as "global pollution" due to their contribution to global climate change (Power et al., 1994).

The popularity of the use of fossil fuels for electricity generation is largely due to their low costs, and will remain as the prime energy provider for meeting society's growing demands (Power et al., 1994; World Energy Outlook, 2004).

1.2.2 CO_2 and Global Warming

Along with its enormous contributions to society's demand for energy, the burning of fossil fuels has resulted in some negative environmental effects. The atmosphere is a 'global commons' that responds to many types of emissions placed into it, as well as changes in the surface beneath it (Karl and Trenberth, 2003). Atmospheric

concentrations of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), have increased since the industrial revolution to the point that significant climate warming and weather changes have been attributed to anthropogenic activity (Bryant, 1997). Methane gas or CH_4 is emitted from human-related activities such as fossil fuel production, fermentation in livestock and manure management, rice cultivation, biomass burning and landfills. However, the CH_4 level in the atmosphere is reported to be 1745 *ppb* (parts per *billion*) – thus making CO_2 the target greenhouse gas for mitigation strategies (IPCC, 2006).

Of all the other greenhouse gases, CO_2 is responsible for about 64% of the enhanced greenhouse effect, making it the focus for the reduction of greenhouse gases (Jepma and Munasinghe, 1998). Figure 1.2 displays the rising atmospheric concentration of CO_2, along with temperature changes, from years 1000 to 2100.

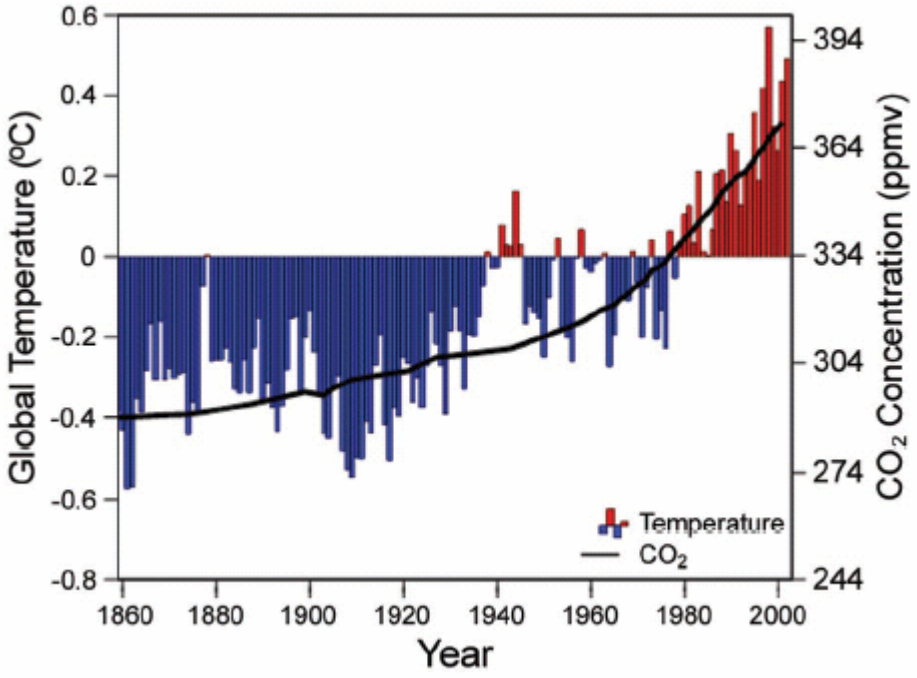

Figure 1.2. Rise in CO_2 levels in the atmosphere

This has contributed to what is known as the earth's "greenhouse effect". An explanation of the "greenhouse effect" is best articulated in Science by Kennedy (2004, p. 1565):

"The basics are straightforward: As we add greenhouse gases like carbon dioxide and methane to the atmosphere, they form a blanket that intercepts infrared radiation as it leaves Earth. This 'greenhouse effect' has been well understood for more than a century. Models that have tracked average global temperature over its fluctuations during the past 10 centuries show that it has followed natural events (such as volcanic eruptions and variations in solar flux) quite well up until the 20th century. Then it entered a rapidly rising phase, associated with an increase in atmospheric carbon dioxide from its pre-industrial level of 280 parts per million (ppm) to the present level of 380 ppm – a value still accelerating as we continue business as usual".

The hypothesis of a large atmospheric temperature increase from greenhouse gases, and further hypothesis that temperature increase will lead to flooding, increases in storm activity, and catastrophic worldwide climatological changes have come to be known as "Global Warming" (Idso, 1997). Active measures for preventing this phenomenon will continue to become more urgent. The suggested solutions presented in this report are the removal of CO_2 from power plant flue gases followed by long term storage.

1.2.3 International Concerns

Numerous research centers consisting of intergovernmental organizations, universities and research centers worldwide have been involved in Carbon Management or

Mitigation projects. Among them are the **Intergovernmental Panel On Climate Change** (IPCC, 2006), **International Energy Agency** (IEA, 2006) and **United Nations Framework Convention on Climate Change** (UNFCCC, 2006).

The **Intergovernmental Panel on Climate Change** (IPCC, 2006) was established in 1988 to evaluate the scientific, technical and socio-economic information necessary for understanding the scientific basis of risk of human-induced climate change, its potential impacts on the environment and options for adaptation and mitigation. The **IEA Greenhouse Gas R&D Programme** (IEA GHG, 2007) was founded in 1991 and is a major international research collaboration that assesses CO_2 fixation technologies that have the potential of reducing greenhouse gas emissions.

The **U.N. Framework Convention on Climate Change** (UNFCCC, 2006), on the other hand, was founded with the objective of stabilizing atmospheric concentrations of CO_2 and other greenhouse gases at levels that will prevent "dangerous anthropogenic interference with the climate system." Actions to implement the UNFCC framework include the organization of meetings and workshops, the development of methodologies to undertake technology needs assessments and the transfer of technological know-how to developing countries.

1.2.4 CO_2 Mitigation: Recovery and Sequestration

The availability of CO_2 fixation technologies would serve as a means to mitigate global climatic change and have become a fast growing research interest. In this report, CO_2 mitigation strategies necessitate a two-stage approach. First, the carbon dioxide gas is captured and separated from the power plant's flue gas. Next, the CO_2

gas is stored in an appropriate "reservoir" to prevent it from entering into the atmosphere. In order to perform a comprehensive study on these technologies, life cycle thinking is employed throughout the research case studies.

1.2.4.1 Brief Introduction to CO_2 recovery systems

CO_2 capture and recovery systems are technically feasible and already employed in many power plants. At present, novel cost effective flue gas CO_2 recovery systems are still being tested and developed (Wong and Bioletti, 2002). The threat of global warming and climate change provides an additional driving force for the development of highly efficient CO_2 recovery systems. Following this, the project will focus on the energy requirements and percentage CO_2 that can be recovered by employing these post combustion technologies.

1.2.4.2 Brief Introduction to CO_2 Sequestration

Carbon sequestration has been proposed as a way to reduce greenhouse gas emissions. According to the **Carbon Sequestration Leadership Forum** (2007), "*Carbon sequestration is a family of methods for capturing and permanently isolating gases that otherwise could contribute to global climate change*". Interest has been increasing in the carbon sequestration option because it is very compatible with large energy production and delivery infrastructures now in place (Khoo and Tan, 2006a; 2006b; O'Connor et al., 2004; Caldeira et al., 2001; Herzog, 1996).

This project will investigate three sequestration alternatives as a means to "get rid" of CO_2: *i) Ocean Sequestration, ii) Geological Sequestration (underground storage),* and *iii) Mineral Sequestration.*

Figure 1.3 gives an overview of the various types of ocean and geological sequestration as a solution to store CO_2 after recovering the gas from the power plant, and Figure 1.4 illustrates CO_2 storage as mineral rocks by mineral sequestration.

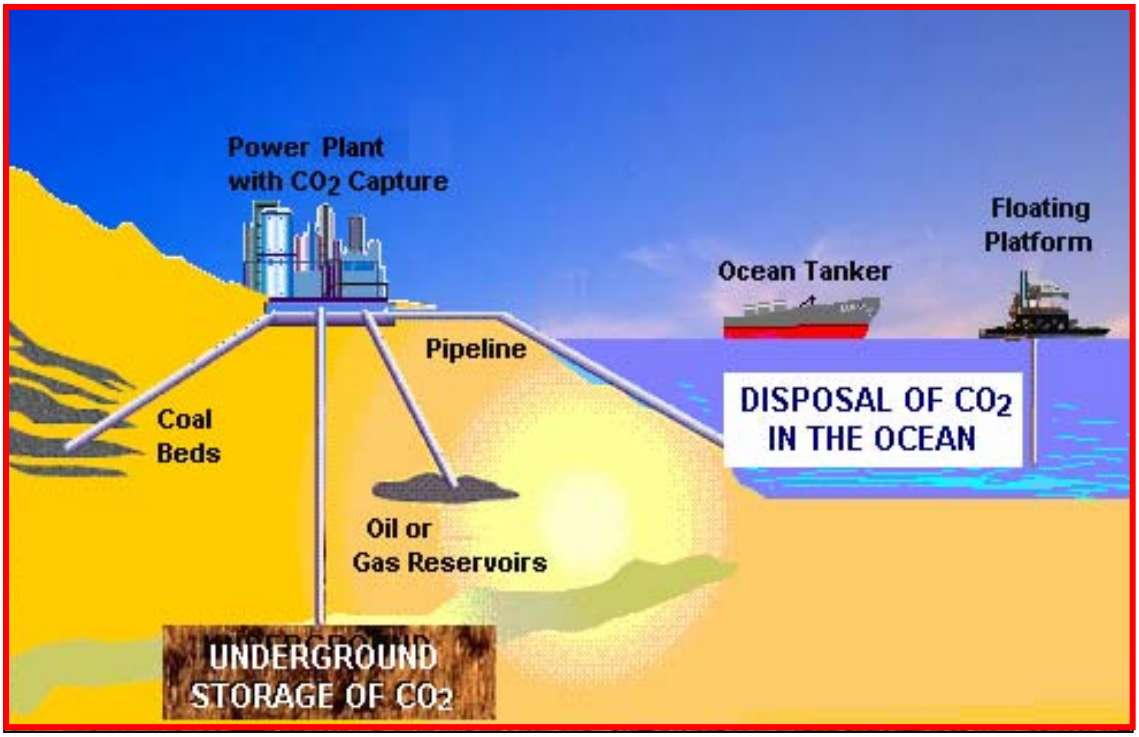

Figure 1.3. CO_2 Sequestration options: Ocean and Geological

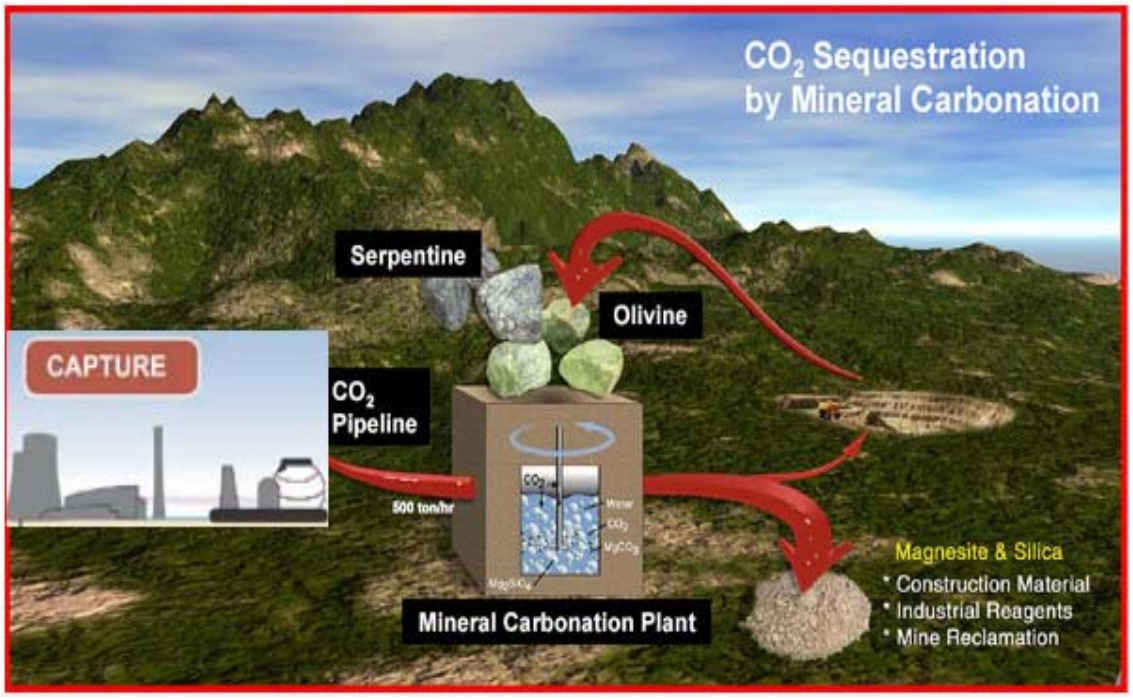

Figure 1.4. CO_2 Sequestration by Mineral Carbonation

1.2.4.3 Preliminary Investigations of CO_2 Mitigation Technologies

Due to the growing interest in carbon mitigation, many feasibility and assessment studies pertaining to CO_2 sequestration methods have been performed. The initial investigations focused mainly on economical and costs assessments or modeling of CO_2 removal systems (e.g., Heddle et al., 2003; David and Herzog, 2000; Biggs et al., 2000). Others discussed various types of transportation methods suitable for carrying CO_2 and the design parameters of pipes suitable for deep ocean injection (Aspelund et al., 2004; Sasaki, 2004; Nihous, 1997; Golomb, 1997). The piping designs, costs and technology required for the transportation of gas used in geological sequestration projects have also been reported (Svensson et al., 2004; Skovholt, 1993). Apart from that, many discussions were presented covering economical feasibility, safety and social issues of geological sequestration (Klara et al., 2003; Aycaguer et al., 2001; Holloway, 1997). As for mineral sequestration, detailed chemical reactions and thermodynamics of the mineral carbonation processes, as well as the costs involved, have been reported by others (e.g., O'Connor et al., 2005; Lackner, 2002; Zevehoven and Kohlman, 2001).

A complete life cycle study of CO_2 recovery and sequestration – from the power plant flues gas to the final storage area – is yet to be reported. This project is the first of its kind to investigate the potential environmental impacts of CO_2 recovery and sequestration technologies, by employing a **Life Cycle Assessment** or **LCA** approach. LCA can be defined as an environmental assessment tool that looks at the "cradle-to-grave" phases of a series of processes or system. Within the system, the input-output flows are identified and compiled, from which, the potential environmental impacts are generated. More details of LCA are given in Chapter 2.

1.3 Research Project Objectives

The author has set forth to investigate the methods and processes involved in reducing atmospheric CO_2. First of all, the series of pollution associated with coal-fired power generation will be presented. Next, in order to reduce the amount of CO_2 generated for every kWh (kilowatt-hour) or MWh (Megawatt-hour) of electricity generated from the power plant, CO_2 capture or recovery technologies should be installed. Finally, various carbon sequestration options will be proposed as a solution to isolate CO_2 from the atmosphere. In addressing climate change or global warming, it is essential that appropriate measurement tools and methodologies are applied to provide an accurate account of the amount of CO_2 that can be potentially reduced.

The project aims to investigate the potential environmental benefits and impacts (or burdens) caused by the application of various CO_2 recovery technologies combined with several CO_2 sequestration methods.

The overall research objectives are to:

- study the chain or series of processes involved to mitigate CO_2, from a cradle-to-grave approach (e.g., starting with CO_2 from the flue gas to final storage site)
- quantify, in the form of input-output data, the environmental consequences of the processes involved in CO_2 recovery and sequestration
- compare existing and proposed technologies
- highlight areas that deserve special attention before the actual large-scale systems are implemented, and finally

- expand the debate on environmental concerns beyond a single issue (global warming/climate change) so that a broader range of environmental issues (resource depletion, acidic and toxic gases, wastes, etc) can be addressed, and unexpected environmental impacts may be revealed.

1.4 Research Approach

In any CO_2 reduction technologies, it is vital to predict if the process of sequestration itself will release more CO_2 into the atmosphere than it promises to prevent. A systems-wide approach must be in place to ensure that the very action taken for preventing climate change does not itself create other (bigger) types of environmental burdens, such as the downstream or upstream release of pollution. Life Cycle Assessment or LCA method satisfies these needs, because it is a holistic method which tracks not only greenhouse gases but also energy consumption, natural resources and all other types of environmental releases (Khoo and Tan, 2006a; 2006b; Tan and Khoo, 2003; Curran, 2000). For the three "components" involved in the project – power plant, CO_2 recovery technology and sequestration method – LCA is used to monitor and evaluate the potential impacts on the environment due to resource and energy usage, the generation of wastes and air emissions and the final amount of CO_2 sequestered or stored.

This is an original LCA investigation where the route of the CO_2 gas is tracked at each stage – from power plant energy generation to CO_2 recovery, pre-processing (liquefaction, compression or sublimation), transportation (ocean tanker or pipeline), and to the final sequestration process. The research overview – or steps involved – is shown in Figure 1.5.

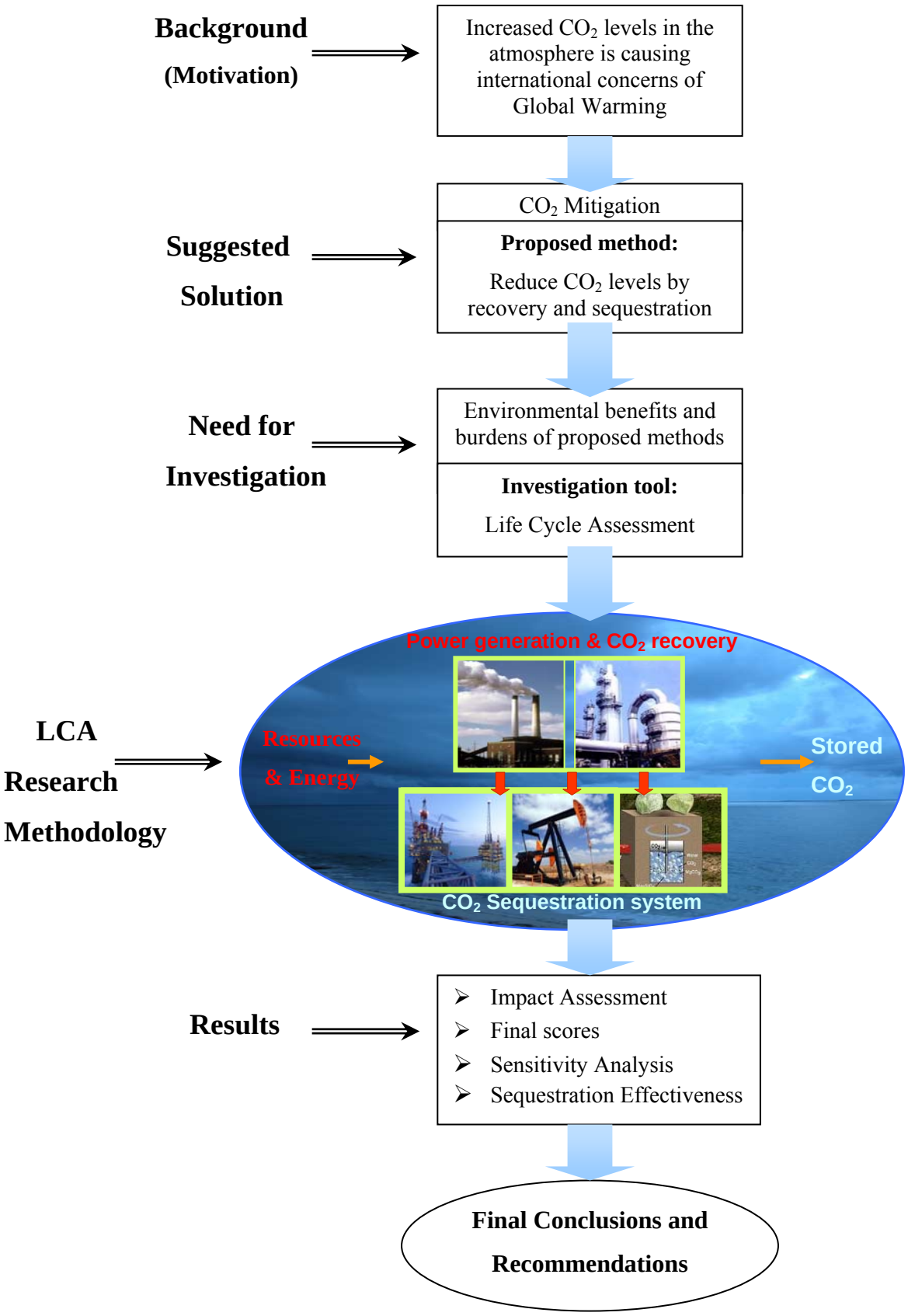

Figure 1.5. Research Overview (steps involved)

1.5 Thesis Layout

In the next chapter, Life Cycle Assessment or LCA is introduced (Chapter 2). The chapter includes the history and evolution of LCA, the methodology, as well as its strengths and various applications in all types of industry. The EDIP 97 impact assessment method will also be presented.

In Chapter 3, coal-fired power and four CO_2 recovery methods are described, including chemical absorption, membrane separation, cryogenic fractionation and physical adsorption (pressure swing adsorption). Also in Chapter 3, five CO_2 ocean sequestration methods, two geological sequestration options, and another five mineral sequestration methods are introduced.

LCA is then applied in detail in Chapter 4 to analyze the three stages, first as three separate or isolated components (sub-systems), and next as an undivided chain of processes (whole system). In the investigation, LCA is first used to study a coal-fired power plant – referred to as LCA Stage 1 – and the four different types of CO_2 recovery technologies – referred to as LCA Stage 2. The final investigation (LCA Stage 3) refers to the comparison of various options for ocean sequestration, geological sequestration and mineral sequestration.

The life cycle impact assessment (LCIA) results are presented in Chapter 5. In this chapter, eight environmental impact categories are interpreted and discussed.

In Chapter 6, further discussions are presented. This is done by first calculating the Final (Weighted) scores of the CO_2 recovery technologies combined with the alternate

sequestration systems. In the same chapter, Uncertainty or Sensitivity Analysis is carried out for: i) higher recovery efficiency rates of the CO_2 removal technologies, ii) different levels of CO_2 per MWh generated from the power plant, iii) different weights (low, medium and high) of the EDIP 97 method, and finally, iv) comparing the EDIP and Eco-indicator method. The Sequestration Effectiveness results for the ocean, geological and mineral sequestration alternatives are also reported.

Finally, in Chapter 7, the final conclusions and recommendations are presented.

CHAPTER 2

Life Cycle Assessment

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Life Cycle Assessment

2.1 What Is LCA

Due to the different characteristics of all three stages involved in CO_2 mitigation – power plant electricity generation, CO_2 recovery systems and CO_2 sequestration methods – a single systematic and unified approach to investigate and evaluate the pollution generated from each stage is called for. A key tool being proposed for this very purpose is LCA or Life Cycle Assessment. LCA is a scientific and technically oriented assessment tool that can help to broaden the environmental management perspective by offering a system's point of view. It has become a worldwide environmental management tool with the advent of the ISO 14040 international standards (Curran, 2000). The LCA impact assessment procedures serve to provide a complete review of the system's activities, including the impending impacts of Global Warming Potential, Acidification, Human Toxicity, Wastes, Resource consumption, etc.

Life Cycle Assessment (LCA) is recognized as a powerful tool for providing quantitative and scientific analyses of the environmental impacts of any industrial systems or products (Tan and Khoo, 2005a; 2005b; 2005c). The LCA methodology and standards provide an adequate instrument for environmental decision support. According to the **United States Environmental Protection Agency** (USEPA, 2005) LCA can be used for "examining the environmental releases and impacts of a specific product [or process] by tracking its development from its raw materials, through its

production and to eventual disposal". The **Society of Environmental Toxicology and Chemistry** (SETAC, 2005), on a similar note, defines LCA as "looking holistically at the environmental consequences associated with the cradle-to-grave life cycle of a process or product".

LCA provides an overall assessment of all environmental parameters, with the purpose of establishing a basis for making the right choices during the development process, thereby producing cleaner technologies or services. The basic philosophy drawn from the principles of environmental management, pollution prevention, cleaner production and industrial ecology have been integrated into various types of LCA studies (Khoo and Tan, 2003; Tan and Khoo, 2006; 2005a; 2005b; 2005c). Built on these principles, the environmental impact assessment throughout the entire life cycle must provide meaningful results to highlight the areas for reducing pollution and waste, preferably at its source, and an overall improved environmental performance for a well-defined system.

The application of LCA is used in a broad range of areas. Among them are: the evaluation of national waste disposal strategies (Tan and Khoo, 2006), environmental risk assessment of chemicals (Olsen et al., 2001), the production and disposal of packaging materials (Tan and Khoo, 2005a), metal recycling activities (Tan and Khoo, 2005b) and the environmental consequences of various types of energy production technologies (Mann and Spath, 2004). In these various applications, life cycle impact assessment results may be calculated to give the total environmental burdens of a system. The "system" in the LCA study may be a manufacturing company, an industry, a new technology or a series of processes.

2.2 LCA: History to present

The origins of the LCA methodology can be traced to the late 1960s, where the waste aspects of manufacturing systems were the main environmental concern. The first ever LCA study was commissioned by the Coca-Cola Company in 1969. Sometime later in 1975, the interest of LCA applications focused on energy usage. And in 1988, the primary interest returned to solid waste, but was quickly replaced by a more balanced concern about the broad areas of resource use and environmental pollution (Hunt and Franklin, 1996).

However, many of the LCA studies were performed using different methods and without a common theoretical framework. Consequently, the results between studies with the same goals often differed considerably, preventing LCA from becoming a more accepted analytical technique. Accompanying the growing activities within the field of LCA, much attention has been paid to the development of a sound methodological basis. SETAC (2005) started work on LCA in 1990 and has since then been the international forum for the discussion of the methodological basis of LCA. In 1993, SETAC published a "Code of Practice" under auspices of ISO, which presents general principles and a framework for the conduct, review, presentation, and use of LCA findings. A general standard for the LCA area with ISO 14040 was adopted in 1997, and more detailed standards for the different phases of the LCA are expected (Klöpffer, 1997).

A summary of the status of LCA, from past to present, given in Table 2.1.

Table 2.1. LCA: History to present

Date	Status
1960s and 70s	First and original study was commissioned by the Coca-Cola Company in 1969. Primary interests were in solid waste aspects of total manufacturing systems.
1980s	Areas of interests broadened to resource use and environmental emissions. This broader interest has sparked the current debate in impact assessment. Also, small-scale development of LCA methodologies and frameworks.
1990 to 1994	Industry, government, and academic interest in LCAs revived on an international scale. SETAC workshops were held to further develop LCA methodologies and practices.
Present	Life cycle thinking and management concepts are Now being widely applied in all areas of industry.

Till today, LCA is internationally recognized as a powerful and scientific tool that can be applied in many areas. These include:

- Design for Environment (DfE) or Eco-labeling
- Industrial Ecology
- Cleaner Production
- Solid Waste management
- Wastewater treatment systems
- Decision support tool for developing environmental policies
- Comparison of energy efficient technologies, etc.

Numerous organizations worldwide are actively involved in the development and use of LCA. Apart from SETAC, the **American Center for Life Cycle Assessment** (ACLCA, 2007) was formed under the auspices of the Institute for Environmental

Research and Education (IERE). The mission of ACLCA is to build capacity and knowledge among LCA practitioners. Some of the organization's objectives are to: i) increase awareness of and to promote the adoption of LCA among industry, government, and NGOs, ii) exchange information relating to LCA, and iii) promote networking among LCA practitioners and researchers.

In the year 1999, the **Australian LCA Network** (2007) was established to globally connect people who are working in or interested in LCA. The network includes projects for the sharing of LCA data or inventory. In Korea, the Ministry of Commerce, Industry and Energy (MOCIE) has undertaken a five-year national research project (1998-2003) to develop LCA data for around 100 modules of representative raw materials, energy, conversion processes, transport and waste treatment methods (UNEP-SETAC, 2006). And in Japan, the **Japan Environmental Management Association for Industry** (JEMAI, 2005) was launched to actively explore and expand the use of LCA in the country.

2.3 LCA Concept and Methodology

According to the ISO 14040 series, the LCA methodology consists of the following phases: Goal and Scope definition and Inventory Analysis (ISO 14041), Impact Assessment (ISO 14042) and Interpretation (ISO 14043). This is shown in Figure 2.1.

Figure 2.1. LCA Stages
[Source: USEPA, 2005]

2.3.1 Goal and Scope

It is important to recognize in the beginning the objectives of the LCA study. Since it is impossible to include every single aspect of the product's life cycle stages in an LCA, some extent of streamlining, boundaries and assumptions will be made (Khoo and Tan, 2003; Tan and Khoo, 2006; Todd and Curran, 1999). This is why it is crucial that the goal and scope of the study are defined in the early stages of the project.

The detailed description of the goal and scope of the LCA studies in this project will be reported in chapter 4.

2.3.2 Inventory Analysis

In this stage, the inputs and outputs of a well-defined system are systematically identified and quantified. These input-output flows are then assessed in terms of their potential to contribute to specific environmental impacts. As a start in identifying the environmental burdens associated with the CO_2 capture and sequestration strategies,

the input-output inventories of a coal-fired power plant will be compiled. The energy requirements for all the processes involved in recovering and sequestering CO_2 will be presented (also in chapter 4).

2.3.3 Impact Assessment (EDIP method)

In theory, impact assessment converts the results from an LCI to a set of common impact measures such as human toxicity, habitat disruption, etc., that can be used to evaluate the total effect of the system in question.

SimaPro, a well established and successful Life Cycle Assessment tool, is used for all the LCA studies presented in this report. This software was developed by a group of LCA consultants (PRé Consultants), which has over 12 years of experience in the field of Life Cycle Assessment and management (SimaPro, 2005). SimaPro's EDIP (Environment Design of Industrial Products) '97 method for impact assessment – that was jointly developed by the Danish EPA, the Technical University of Denmark and Confederation of Danish Industries – will be used to calculate the results for the following environmental impact categories: Global Warming Potential (GWP), Acidification, Human Toxicity (air and water), Eutrophication, Ecotoxicity (water acute), Wastes and Resources. This method for calculating the potential impact assessment of products of processes is developed in line with the ISO standards.

The EDIP is a problem-oriented (mid-point) method which is widely used and highly recognized by many LCA experts, including Huijbregts et al. (2005), Tan and Khoo (2006), Corrado et al. (2006), and Lu et al. (2006).

The impact assessment involves three main steps (SimaPro, 2005): i) characterization or classification, ii) normalization and final weighted scores.

2.3.3.1 Classification and Characterization

In the first step, the classification and characterization of impacts consists of the analysis and estimation of the magnitudes of the potential environmental burdens. For example, for greenhouse gases, the calculation of GWP is based on a number of factors, including the radiative efficiency or heat-absorbing ability of each gas relative to that of carbon dioxide, as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of carbon dioxide (IPCC, 2006).

The aim here is to model the categories in terms of indicators so that there is a basis for comparison within the individual categories. For example, greenhouse gases, such as CO_2, CH_4 and N_2O contribute to the global warming impact category and are placed together under the same "class".

The scientific explanation is as follows. On a mass basis, and for a 100-year timeframe, methane (CH_4) absorbs 25 times as much of the earth's outgoing infrared radiation as CO_2. Therefore, in terms of CO_2-equivalent (or CO_2-eq), CH_4 is designated an equivalency factor or *characterized factor* of 25. An exact definition of how GWP is calculated is to be found in the IPCC's ***2001 Third Assessment Report.*** Figure 2.2 below shows how greenhouse gases are assigned to a specific impact category, e.g., Global Warming Potential (GWP).

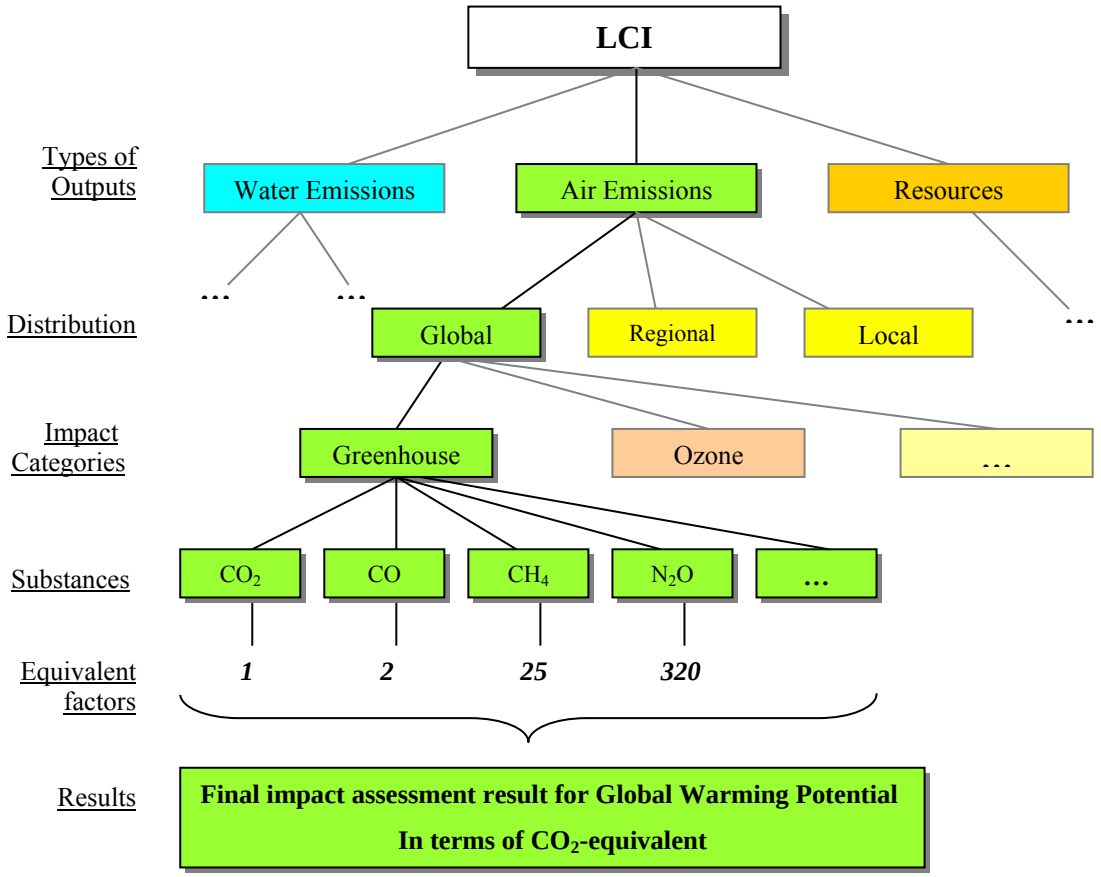


Figure 2.2. Impact assessment steps for calculating Global Warming Potential (GWP) results

The characterization stage has lead to a great deal of effort carried out by environmental scientists and experts (e.g., Huijbregts et al. 2005) on the development of the aggregation of the impacts on the basis of equivalency factors such as human toxicity levels, eutrophication, ecotoxicity, acidification, etc. Essentially, these would allow for each of the individual substances or pollutants to be added to produce an overall impact assessment result for the category (Hofstetter, 1999).

2.3.3.2 Normalization and Weighting

The normalization step is performed to provide the relative size of each environmental impact. This means the impact category is divided by a reference number. The reference may be chosen by assessing the average yearly environmental load in a country or continent, and then divided by the number of inhabitants. In the final stage, the normalized scores are multiplied by a weighting factor to give the Final weighted (combined) scores that represent the relative importance of the total environmental impact.

By multiplying the characterized results with the Normalized values and Weights, the Final Scores can be obtained. The characterization factors, normalization values and weightings for the EDIP method – for selected pollutants – are contained in **Appendix A**. These values are derived by LCIA consultants and environmental experts who employ a multidisciplinary scientific approach for studying environmental models (on air, sea, land) combined with the application of what is known as "proxy indicators" for: the emitted volume of a certain pollutant per year (in a selected region), mobility, persistency and accumulation; and their final adverse effects (i.e., toxic effects on humans or ecosystem) (Hofstetter, 1999).

2.3.4 Interpretations

There are many ways to interpret an LCA study based on its results. For the first round of impact assessment calculations, the ***characterized results***, that is, total impacts in terms of CO_2-eq, SO_2-eq, etc., will be presented. Next, further interpretations are made based on the generation of Final Scores (end point results), Sensitivity Analysis (or Uncertainty Analysis) and Sequestration Effectiveness.

2.3.4.1 Mid-point vs. End-point results

The EDIP is a "mid-point" method and has the ability to generate reliable and scientifically acceptable results. The impact assessment methodology is illustrated below in Figure 2.3.

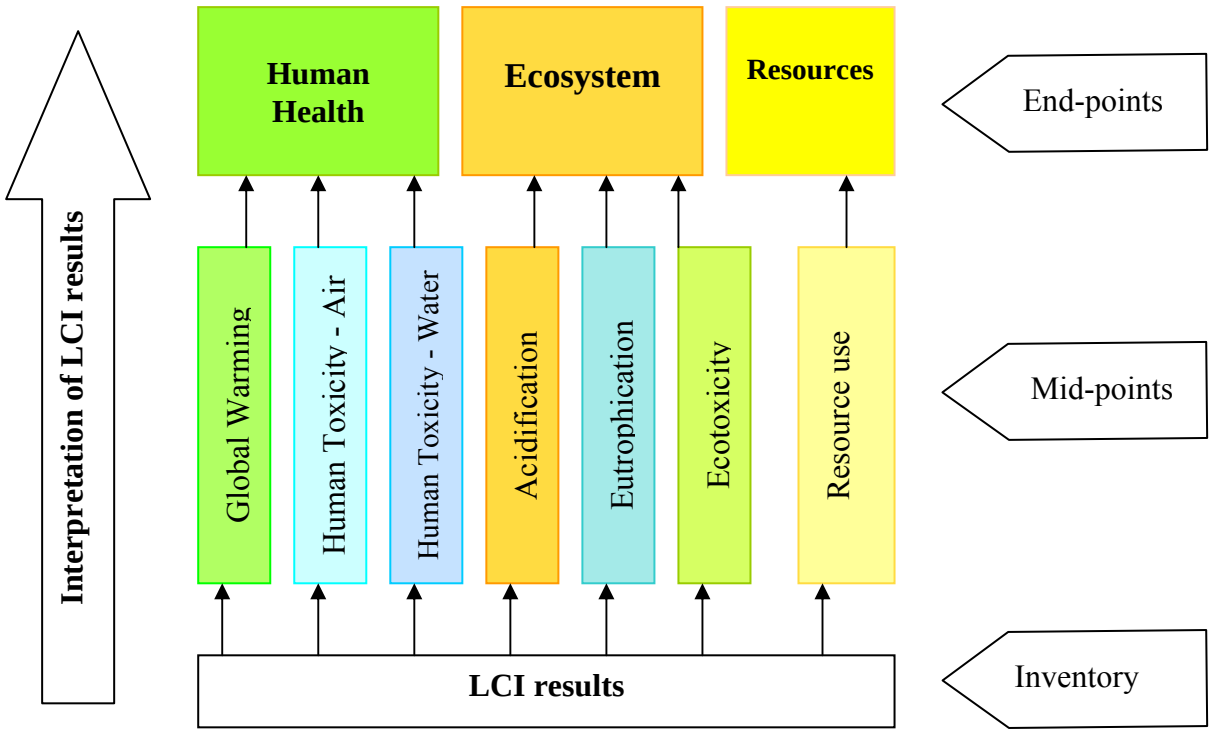


Figure 2.3. Interpretation of results: mid-point vs end-point impacts

The graphs of the results can be interpreted in the following manner. Positive graphs generated for Global Warming, Human Toxicity (Air and Water), Ecotoxicity, Resources use, etc., depict the amount of environmental burdens or destruction that could have potentially taken place due to the application of the CO_2 recovery technologies or CO_2 sequestration processes. Negative peak shown on the graphs imply the possible *prevention* of any environmental damage. This may be due to the successful isolation of CO_2 from the atmosphere, or due to the recovery of resources.

These results will be presented as chapter 5.

2.3.4.2 Final Scores and Sensitivity Analysis (Uncertainty Analysis)

The final weighted scores for the LCA studies are able to provide the "overall picture" of whether or not the entire system under investigation results in environmental burdens (shown by positive scores) or environmental benefits (negative scores). Sensitivity Analysis and Sequestration Effectiveness will also be presented. The details will be in Chapter 6.

2.4 Strengths of LCA

The power of LCA is that it expands the debate on environmental concerns beyond a single issue (global warming/climate change), and attempts to address a broad range of environmental issues (acidification, resource use, etc). By providing a system's view of the entire process, the emissions generated and wastes discharged, as well as, the resources consumed by a series of processes or a system can be quantified systematically.

The author (Khoo and Tan, 2006a; 2006b; 2006c; Tan and Khoo, 2006; 2005a; 2005b; 2005c) has successfully applied LCA in various case studies for comparing and identifying the most environmentally suitable strategy at an early stage, the best practicable environmental action or alternative combination of processes/technologies. Figure 2.4 gives an overview of LCA thinking applied in CO_2 management – starting with coal mining, to transportation, next to electricity generation and CO_2 recovery, ocean tanker transport, and finally to its storage media (e.g., deep ocean).

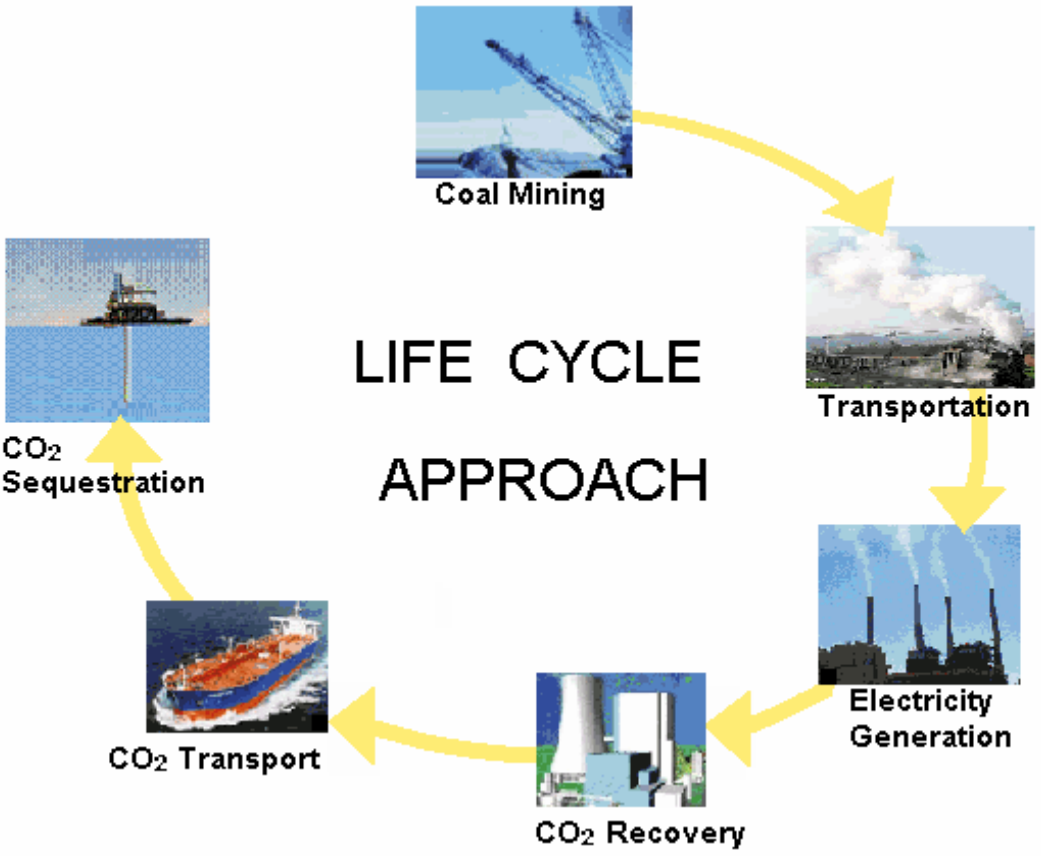


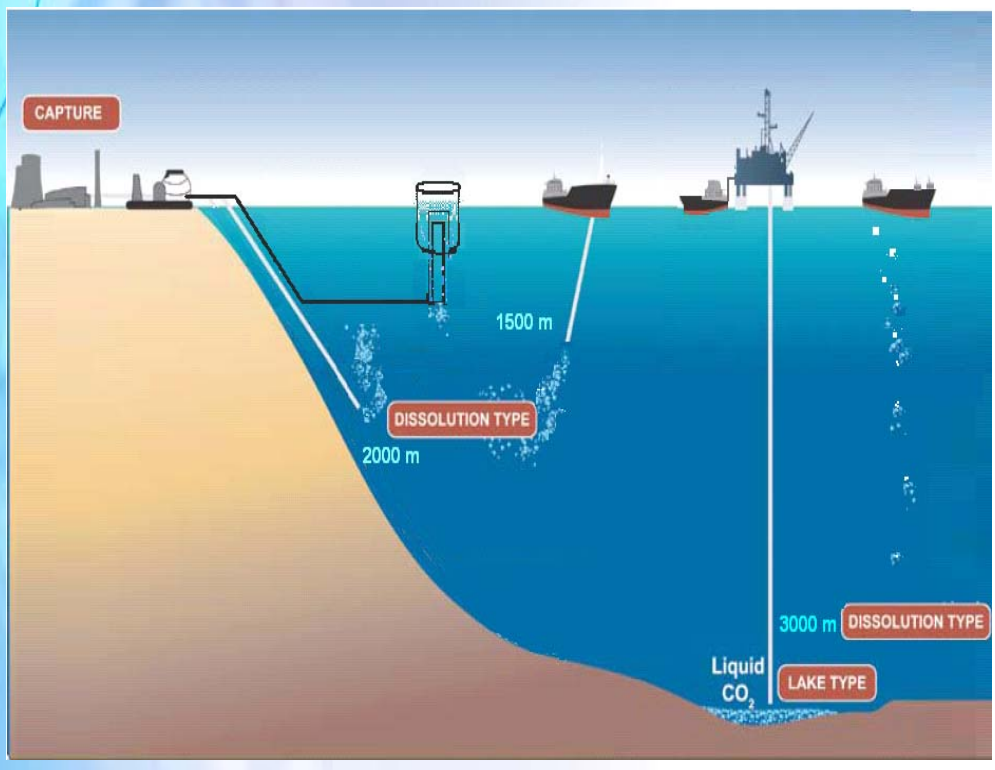
Figure 2.4. Life Cycle Approach – cradle-to-grave investigation of CO_2 recovery and sequestration

Although biological sequestration is another potential approach that can be employed for CO_2 fixation, this method is not included in the research work due to lack of hard data and the information required for carrying out a feasible LCA study.

The detailed description of four types of CO_2 recovery technologies and three types of CO_2 sequestration options – ocean, geological and mineral storage – will be described in the next chapter.

CHAPTER 3

Electricity Generation, CO_2 Recovery and Sequestration



CHAPTER 3

Electricity Generation, CO_2 Recovery and Sequestration

3.1 Coal-fired electricity generation and CO_2 emissions

Coal is an important source of electricity generation in a number of the world's regional markets. In the U.S. alone, about one-half of its total electricity is generated from coal-fired power plants. Coal also accounts for 43% of South Asia's energy consumption. In the year 2003, the United States consumed 1.1 billion tons of coal, accounting for 92% of total coal consumption in North America and 44% of the OECD total (EIA, 2006).

Coal has the highest carbon intensity among fossil fuels, resulting in coal-fired plants having the highest output rate of CO_2 per kilowatthour (kWh). The U.S. generates over 1.6 GT (Giga-ton or billion metric tons) of CO_2 is produced each year from power plants, namely from coal-fired power plants (Herzog, 1996). As an example, a 1000 MW pulverized coal fired power plant can emit up to 6-8 Mt of CO_2 annually, an oil-fired power plant about 25% less, and a natural gas combined cycle power plant about half of the CO_2 emissions that come from coal powered plants (Herzog and Golomb, 1996). This makes coal-fired electricity generation system the main reference for the analyses of various CO_2 capture studies, along with carbon sequestration methods (Wilson et al., 1992; Hendriks, 1995; Gielen, 2003).

Coal-fired electricity is selected as the main energy resource in evaluating and comparing the project's CO_2 recovery and sequestration systems.

3.2 CO_2 Recovery

CO_2 can be separated and captured as a by-product of fossil fuel from energy combustion (coal-fired power plants). Currently a variety of technologies are in use or under development for separation and capture. The following presents basic descriptions of the latest four post-combustion capture technologies: chemical absorption, membrane separation, cryogenic fractionation and physical adsorption.

3.2.1 Chemical Absorption

Chemical Absorption of CO_2 by the use of an amine or carbonate solvents is the most well established method of CO_2 capture in many commercial power generating plants. Prior to CO_2 removal, the flue gas is cooled, then treated to reduce particulates and other impurities. Next, the gas is passed into an absorption tower where it comes in contact with the absorption solution. The gas reacts with the chemical solvent to form a compound which is then broken down by the application of heat, regenerating the original solvent and producing the pure CO_2 stream. Typical solvents are Monoethanolamine (MEA), diethanolamine, ammonia and hot potassium carbonate. At the final stage, the CO_2-rich solvent is pumped into the stripper tower where the pressure is reduced and/or the temperature is raised to approximately 120 °C to release the pure CO_2 gas. As the gas is compressed, the regenerated absorbent is recycled back to the absorber, where the process is repeated in a continuous cycle (Hendriks, 1995; McKee, 2002).

Since CO_2 absorption takes place when gas and liquid phases are brought into contact, efficiency of the absorption process is therefore dependent upon the degrees of gas-

liquid contact provides by the column. CO_2 recovery rates of 95-98% can be achieved by using amines, and product quality can be in excess of 99% (Wilson et al., 1992). Chemical absorption processes need heat for regeneration. The energy demands are estimated to be 330-340 kWh per ton CO_2 recovered; these values are for both heat requirements and solvent re-generation (Göttlicher and Pruschek, 1997; Bolland, 2005). It is assumed that the solvent (MEA) is completely recycled in the process, the only emissions generated in this technique are those caused by energy use. A schematic diagram of an amine separation process is shown in Figure 3.1 below.

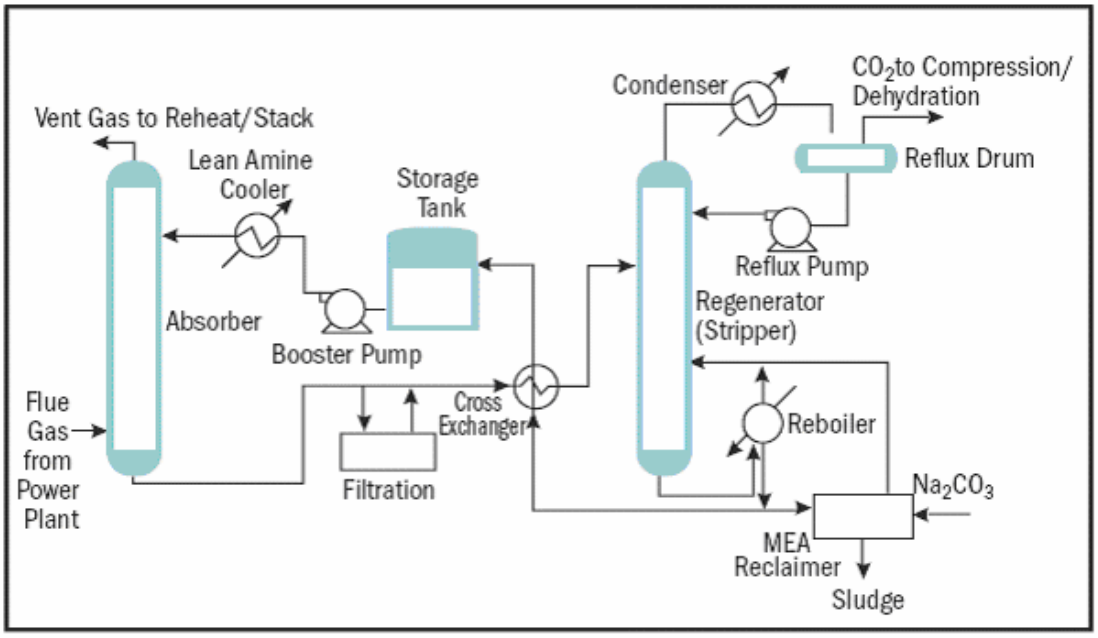


Figure 3.1. CO_2 capture and recovery by chemical absorption (amine separation)

[Source: McKee, 2002]

3.2.2 Membrane Separation

Membranes are barrier films that allow selective and specific permeation under conditions appropriate to its function. This working concept is shown in Figure 3.2. Typical membrane materials are polymer or ceramic. This technology is primarily a

physical process which allows CO_2 to pass through the membrane wall while excluding the other parts of the flue gas emitted from the power plant. The effectiveness of this recovery process relies on the differences in physical or chemical interactions between various substances in a gas mixture and a membrane material. Usually, multiple stages or recycling of one of the streams is necessary. Membrane systems are relatively simple modular methods that do not require a great deal of associated hardware (McKee, 2002). Commercially available polymeric gas separation membranes are mostly used, with energy demands of 70 to 75 kWh per ton of recovered CO_2 (Göttlicher and Pruschek, 1997). Typical removal rates are approximately 82-88% of CO_2 from the power plants' flue gases (Audus, 2000; Gielen, 2003). The main air pollution generated from this technology is from energy use.

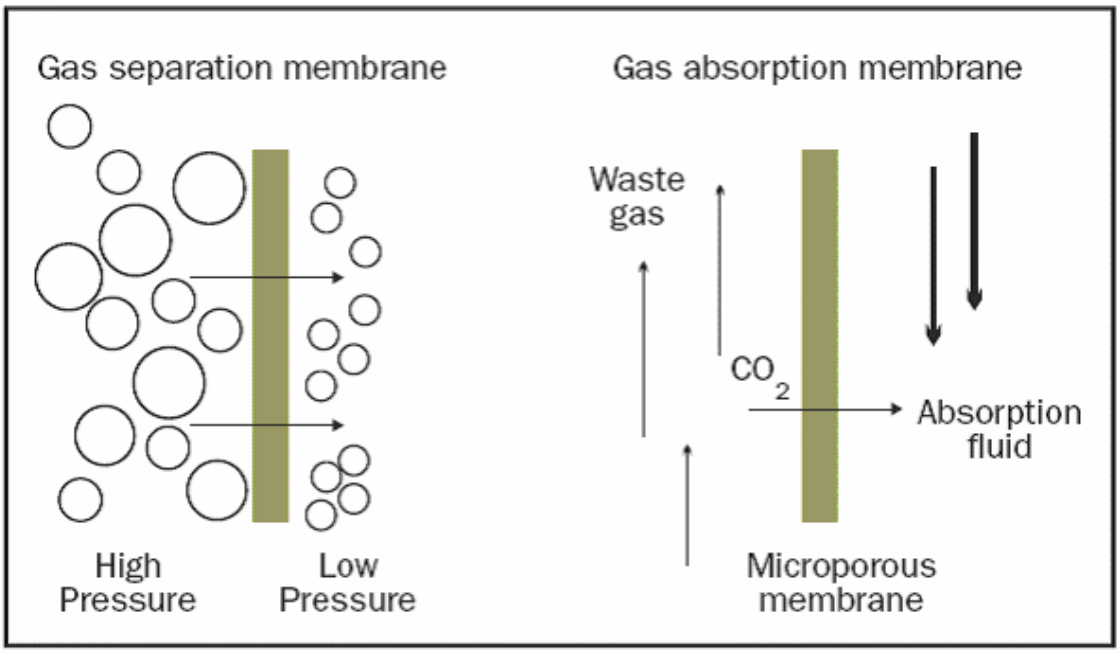


Figure 3.2. Membrane separation concept

[Source: McKee, 2002]

The commercial membranes for CO_2 separation are mainly prepared from cellulose acetate, polysulfone and polyimide. Compared to absorption separation technologies, the advantages of the membrane separation process are as follows (Wong and Bioletti, 2002):

- Regeneration is not required
- The systems are compact and lightweight
- Modular designs can allow the optimization of process arrangement by using multi-stage operation
- Low maintenance requirements because there are no moving parts in the membrane unit.

3.2.3 Cryogenics

Cryogenic fractionation can separate CO_2 from other gases using pressure and temperature control. In a cryogenic separation system, CO_2 is physically separated from other gases by condensing it at an extremely low temperature. Cryogenics is also known as low temperature distillation and is a commercially available technology commonly used to liquefy and purify CO_2 from relatively high purity sources. It involves cooling the gases to a very low temperature so that the CO_2 can be cooled and separated. A cryogenic separation plant is expensive and large and the distillation column is several stories high and must be well-insulated. Consequently, it is more economically feasible to separate the CO_2 gas in huge amounts (Dijkstra and Jansen, 2004). The amount of CO_2 recovered is approximately 90-95% of the flue gas. The energy requirements are estimated to be 600-660 kWh per ton of CO_2 recovered as a liquid form (Göttlicher and Pruschek, 1997). Once again, the main air pollution

generated from this technology is from energy use. The cryogenics process is displayed in Figure 3.3.

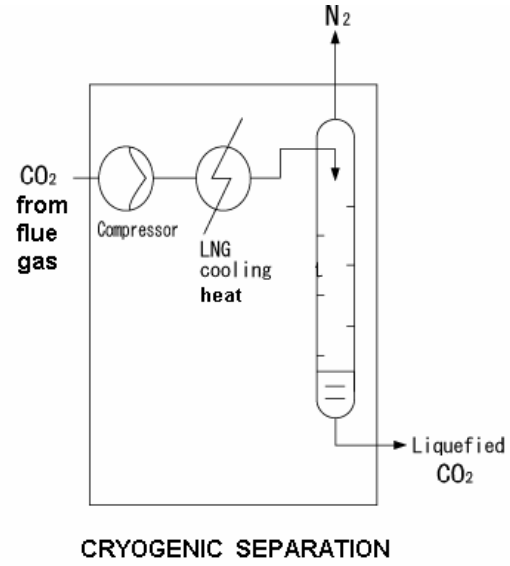


Figure 3.3. Cryogenic fractionation process

3.2.4 Pressure Swing Adsorption

Some materials with high surface areas, such as zeolites and activated carbon, can separate CO_2 from gas mixtures by physical adsorption. An example of this application is Pressure Swing Adsorption (PSA), which is a commercially available technology for capturing or recovering CO_2 from power plants. A typical PSA unit consists of a series of vessels, each containing the same type of adsorbing media such as granular alumina molecular sieve or activated carbon. The gas flows through a packed absorbent bed at elevated pressure and low temperature until the adsorption of the desired gas approaches equilibrium conditions at the bed exit (McKee, 2002). A schematic diagram of this CO_2 recovery system is displayed in Figure 3.4.

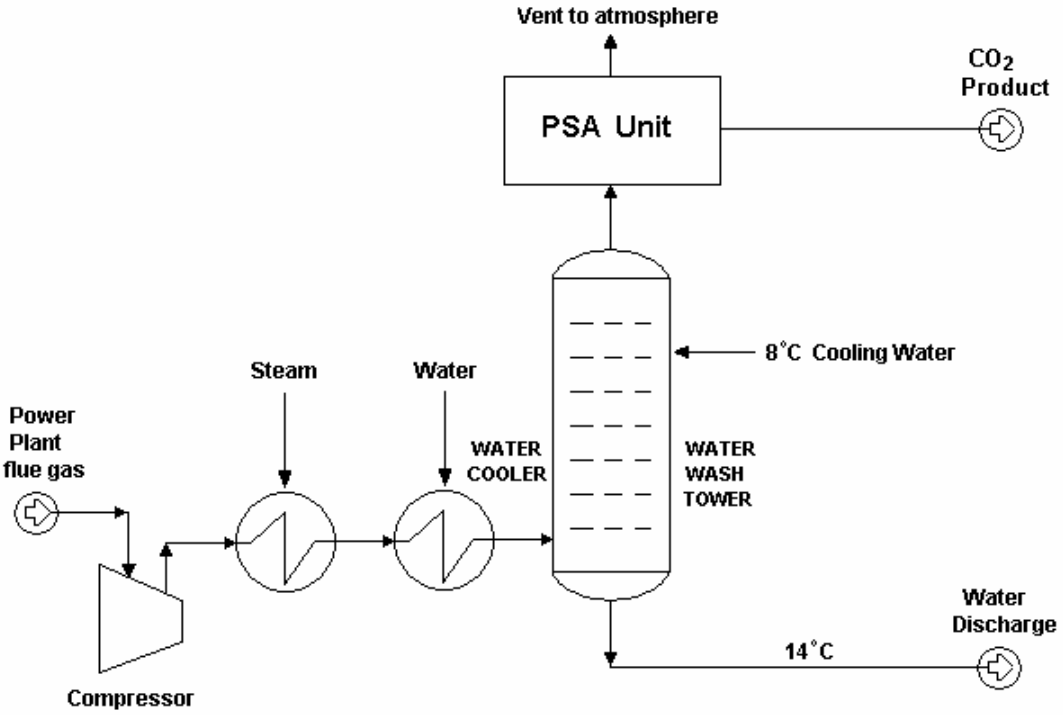


Figure 3.4. Typical layout of a CO_2 capture plant using physical adsorption

[Source http://www.ieagreen.org.uk]

As shown in Figure 3.4, the process operates on a repeated cycle with the basic steps being adsorption and regeneration. Critical adsorption variables include temperature, partial pressures, surface forces and adsorbent pore sizes. The main advantage of physical adsorption over chemical absorption is its simple and energy efficient operation and regeneration. It is known to be one of the most economic processes to recover CO_2 in flue streams from power plants. By the use of one stage with two adsorbent columns, the recovery of the CO_2 gas can be in the range of 85-90% with energy demands from 160-180 kWh/ton CO_2 recovered (Göttlicher and Pruschek, 1997; Takamura et al., 2001). The only emissions generated in this technique are those caused by energy use.

The four CO_2 recovery technologies – chemical absorption, membrane separation, cryogenics and PSA – serve the purpose of capturing or recovering the greenhouse gas from the power plant's flue gas. Next, this recovered CO_2 must be stored to prevent it from accumulating in the atmosphere. This is known as CO_2 sequestration.

3.3 Ocean Sequestration

It was suggested by several scientists (Marchetti, 1977; Ozaki, 1997; Caldeira et al., 2001) that the ocean, which occupies more than 70% of the earth's surface, is the largest buffer to "dump" and store CO_2. The use of the deep oceans had been proposed as early as 1977 (Marchetti, 1977), as a possible disposal medium for anthropogenic carbon dioxide.

It was estimated that the ocean already contains an estimated 40,000 GtC (billion tons of carbon) compared with 750 GtC in the atmosphere and 2,200 GtC in the terrestrial biosphere. As a result, the amount of carbon that would cause a doubling of the atmospheric concentration would change the ocean concentration by less than 2% (Herzog, 1996; 2001). However, there has been concerns about the increase of the hydrogen-ion activity of ocean waters (decreasing ocean pH), which makes the oceans more acidic due to excessive CO_2 intakes. Nevertheless, many scientists still remain confident about the ocean's ability to sequester CO_2 in a safe and acceptable manner (Tsouris et al., 2004; Caldeira et al., 2001; Kosugi et al, 2001; Bacastow et al., 1998).

CO_2 gas is constantly being exchanged between the ocean and the atmosphere. Because of this exchange, questions arise as to how effective the ocean will be as a choice to store CO_2 and keep it from re-entering the atmosphere (Herzog et al., 2001).

Although this field is still in its infancy, international interest has been increasing, mainly in various parts of U.S., Europe and Japan. Several pilot tests and experiments have been performed to investigate the behavior of CO_2 in various depths of the ocean. Under high pressure or low temperatures, CO_2 becomes liquid. At ocean depths of 1000m to 1500m, liquid CO_2 will diffuse as droplets. As for depths greater than that, the high density CO_2 will display negative buoyancy and hence sink to the ocean floor to form a CO_2 lake (Kheshgi et al., 1994; Millero, 1995; Caldeira et al., 2001). The lake formed is maintained in place by a surface pavement and a subpavement cap of CO_2 hydrate ($CO_2 \cdot 6H_2O$) that traps the low-density liquid CO_2 in place.

Herzog et al. (2001) projected through scientific experiments (for example, building numerical ocean models) that the amount of time over which the percentage of the injected CO_2 would be sequestered permanently would depend largely on the injection or disposal depths. It has been estimated that at depths of 1500m, 2000m and 3000m, approximately 74%, 81% and 90% of CO_2 respectively will be remain stored, or completely dissolved in the ocean for at least 500 years. This makes CO_2 ocean sequestration a promising technology that allows the disposal of CO_2 in large quantities.

Five case studies are presented for ocean sequestration. They are known as: Vertical Injection, Inclined Pipeline, Pipe Towed by Ship, Dry Ice and Gas-lift Advanced Dissolution or GLAD system.

3.3.1 Vertical Injection

In the first ocean sequestration option, Ozaki et al. (1995) and Herzog (1999) introduced the injection of CO_2 into the ocean depths of 3000m from a vertical pipe hanging from a floating platform. In this option, CO_2 gas is first recovered from the power plant flue gases and liquefied, after which it is transported by an ocean tanker for a distance of 100 km to a floating platform. From the platform, a long vertical pipe is used to inject the liquefied CO_2 directly into the ocean. At the injection depth of 3000m, 90% of the CO_2 will be expected to be stored for at least 500 years (Herzog et al., 2001).

Preliminary theoretical studies appear to show that permanent storage of CO_2 is possible. The pressure at the depth of 3000m turns the CO_2 into a clathrate. This clathrate formation can be expressed by the following formula (Murray et al., 1996):

$$\boldsymbol{CO_2\ (l) + 5.75\ H_2O\ (l) = CO_2\text{-}Clathrate\ (s)}$$

This compound is a solid under conditions of temperature and pressure at deep ocean depths, and has higher density than seawater. It is predicted that most of the CO_2-clathrate will remain at the bottom of the ocean.

Technical details of the piping material, length and stress, as well as pumping pressure requirements can be found in Ozaki et al. (1995). Further discussions relating to the technological and engineering challenges faced for transporting liquid CO_2 to the ocean sites have been discussed by Nihous (1997). The energy requirement for liquefaction is estimated to be 120 kWh per ton CO_2 (Göttlicher and Pruschek, 1997). Energy requirements for compression and injection from the floating platform

are estimated to be about 40-50 kWh per ton CO_2 (Sasaki, 2004). Figure 3.5 gives the details of the entire process chain, starting from the power plant flue gas to the stored CO_2 in the ocean depths.

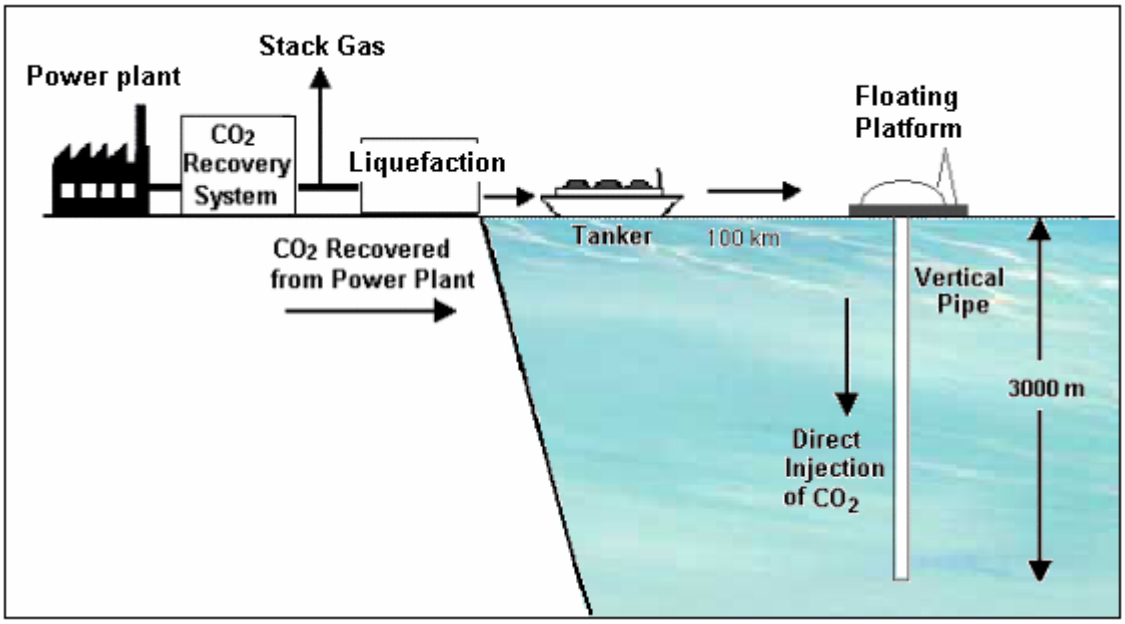


Figure 3.5. Vertical Injection of liquid CO_2 from a Floating Platform

3.3.2 Inclined Pipeline

In the second option, shown in Figure 3.6, compressed CO_2 is pumped into a depth of 2000m into the oceans via a long inclined pipe (Golomb, 1997). At this injection depth, it is estimated that 81% of the gas will remain sequestered for 500 years, and the rest (19%) will leak into the atmosphere (Herzog et al., 2001). Dense phase transportation of CO_2 by offshore pipeline is not a new engineering concept and has been employed for more than 30 years by gas and oil companies. Seabed pipelines, about 0.5m in diameter, have been constructed to handle gases and liquids at depths of 1500m – 2000m. This makes the CO_2 pipeline method a feasible one, as long as the environmental impacts (on marine life) has been thoroughly investigated and confirmed to be acceptable.

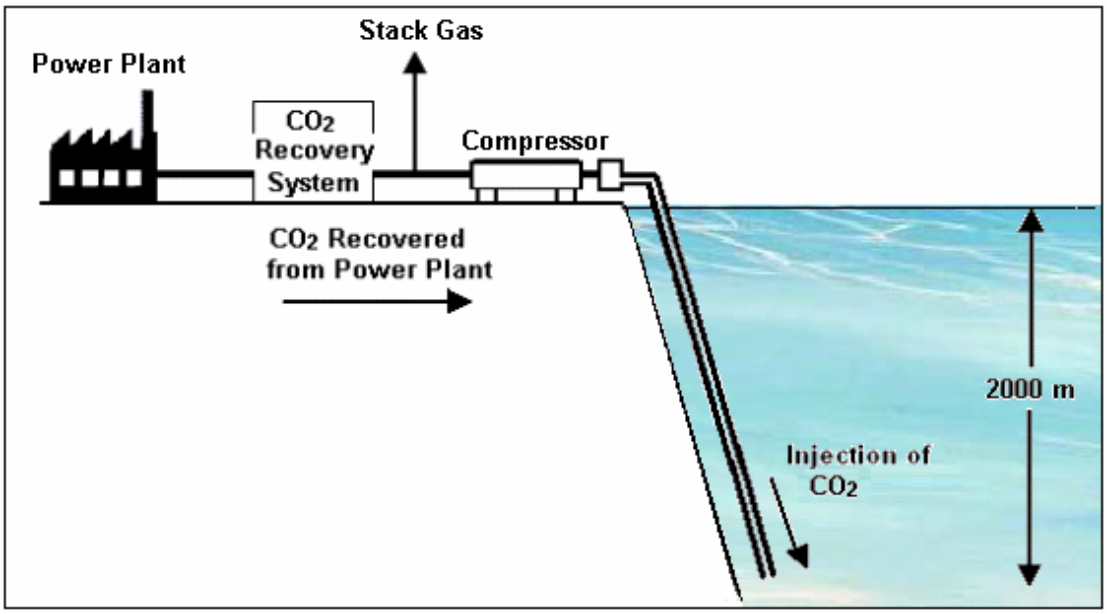


Figure 3.6. Injection from an Inclined Pipeline

This option is feasible for power plants that are located near ocean shores. In this case, CO_2 may be transferred via pipeline in a compressed form. This is because liquefaction of CO_2 is only needed for ocean tanker transportation. Compression of CO_2 pipeline transportation (for distances of 250-500 km from the power plant to the offshore site) can be up to 100 kWh/t of CO_2 (Aspelund et al., 2004). At the sequestration site, re-compression is required before the final injection, which takes up to 30-40 kWh/ton CO_2 (Sasaki, 2004). The energy required for re-compression is less than the first stage of compression. At the end of the pipe, the gas does not necessarily have to be in a highly compressed state.

3.3.3 Pipe Towed by Ship

In the third case, liquefied CO_2 is loaded onto a ship or ocean tanker, transported for an estimated distance of 300 km, and then injected into the ocean via a pipe suspended from the ship. In this manner, the gas is injected. The process chain of

this system – starting from the power plant, CO_2 recovery, liquefaction, loading and final injection – is displayed in Figure 3.7.

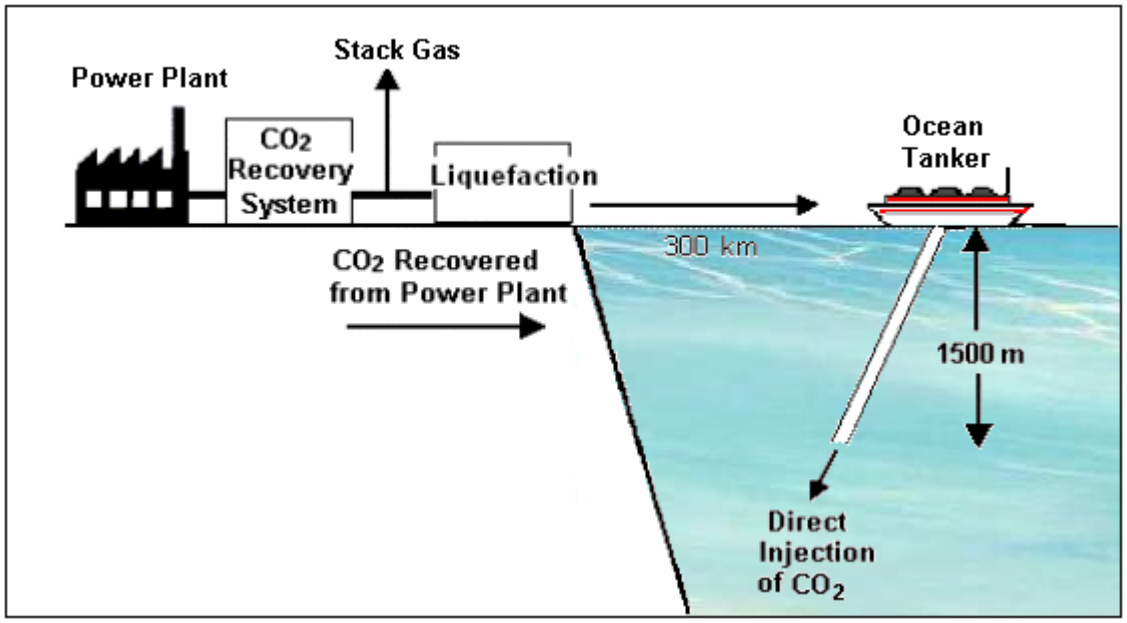


Figure 3.7. Injection of liquid $CO_2$from a pipe towed by a ship

The estimated energy for compression and injection from the ship is roughly 25-30 kWh per ton CO_2 (Sasaki, 2004). The engineering feasibilities of the pipe-towing capabilities and design have been investigated by Minamiura et al. (2004). The authors have calculated the basic details of the pipe's bending and axial strength, inclination angle (θ) and the weight of the pipe itself. These design parameters are illustrated in Figure 3.8.

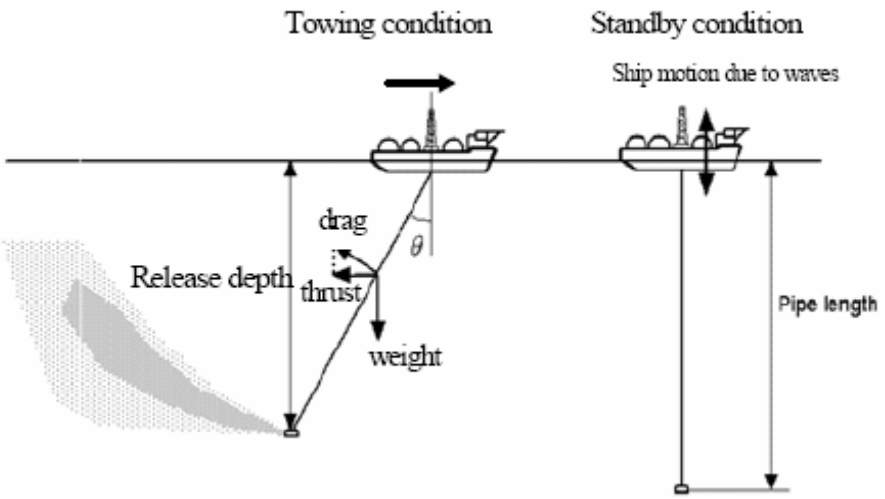


Figure 3.8. Basic conditions considered in the feasibility investigation of a pipe towed by ship [Source: Minamiura et al., 2004]

Further experiments were performed to estimate the behavior of the CO_2 droplets after being released into the ocean. Minamiura et al. (2004) envisaged that the released CO_2 from the pipe will first forms droplets, which will then rise gently due to their buoyancy. As the droplets rise, their size would be reduced through dissolution, and will eventually disappear into the ambient seawater. In this manner, CO_2 is injected at 1500m into the ocean where roughly 74% of it remains trapped for 500 years (Herzog, 1999; Herzog et al., 2001).

3.3.4 Dry Ice

In the fourth proposal, solid CO_2 or dry ice blocks are disposed into the ocean from a moving ship. Solid CO_2 has a specific gravity of 1.5 and will readily sink (Millero, 1995). It has been suggested that this option may pose the least environmental impact in the ocean, however, the process for making dry ice (sublimation) takes up twice the energy of that required for CO_2 liquefaction (Fujioka et al., 1997; Gambini and

Vellini, 2000). In this ocean sequestration option, shown in Figure 3.9, the estimated travel distance of the tanker is 300 km, where the CO_2 blocks are assumed to reach complete dissolution at depths of 3000m (Johnston et al., 1999). The sublimation process takes up an energy penalty of 240 kWh/ton CO_2.

The technique proposed would depend on the fact that CO_2 can be obtained as a solid by cooling it to -78.50 °C. The overall specific gravity is approximately one and a half times that of seawater. Preliminary tests have shown that if produced as a solid, CO_2 blocks would fall through the water and would slowly dissolve on the sea floor. This conclusion is based on studies using penetrator technology that were investigated as a disposal option (Murray et al., 1996).

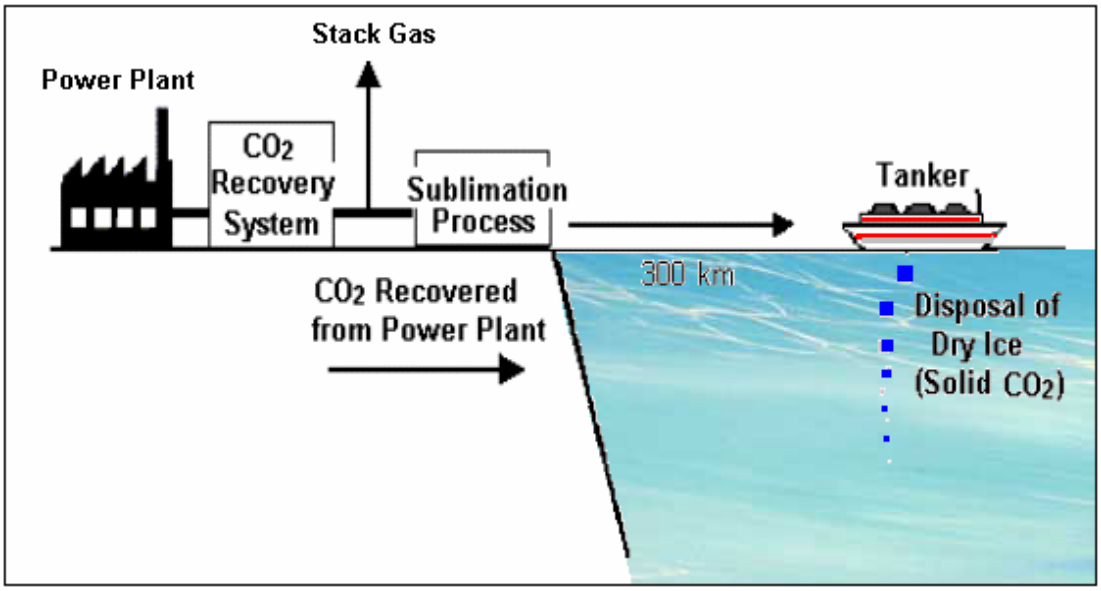


Figure 3.9. Disposal of Dry Ice (Solid CO_2 Blocks)

3.3.5 GLAD

The final carbon ocean sequestration method is proposed by Kosugi et al. (2001), for the sequestration of low purity CO_2 gas. After the CO_2 gas is recovered from the

power plant, it is passed directly to a gas-lift pump system, named gas lift advanced dissolution or GLAD. The GLAD system first dissolves the CO_2 into seawater at a relatively shallow depth of 200–300m and then transports CO_2-rich seawater to depths of 1000-3000m. The GLAD system has been tested by numerical simulation and is claimed to offer mechanical advantages of simplicity of construction as well as flexibility in operation (Kajishima et al., 2004). The GLAD system is displayed in Figure 3.10.

An advantage of the GLAD method is that it bypasses the need to liquefy CO_2, which is a process that consumes a large amount of energy. The energy requirement for the compression for the GLAD system is 3.7 kWh per ton CO_2 (Niwa, 2004). It is assumed for this case that the CO_2 gas reaches complete dissolution at an average depth of 1500m, where 74% is expected to remain sequestered.

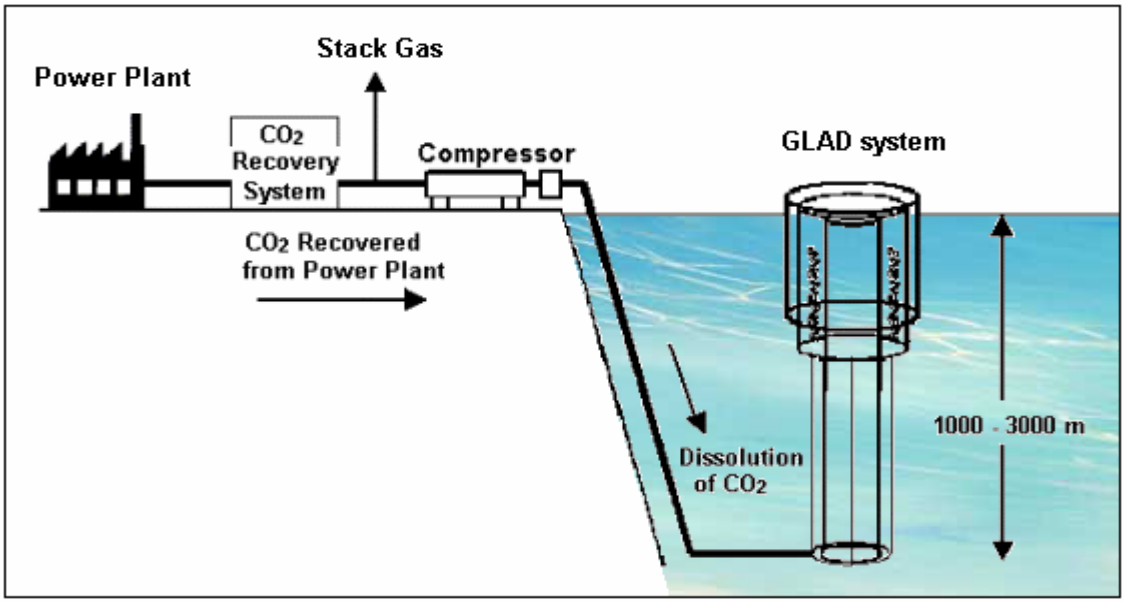


Figure 3.10. Dissolution of gaseous CO_2 by GLAD system

3.4 Geological Sequestration

Geologic sequestration of CO_2 involves storage of the greenhouse gas in underground formations, after it has been captured from power plants or other large industrial facilities. It is an idea that is being pursued around the world in view of its potential to deliver significant reductions in CO_2 emissions. As part of a broader portfolio of technologies, geologic sequestration appears to be capable of playing an important role in stabilizing CO_2 concentrations in the atmosphere.

The most important geological media for geologic sequestration are deep coal seams, saline aquifers, and depleted oil and gas reservoirs (Klara et al., 2003). The estimated capacity of geologic storage for CO_2 sequestration is reported to be as high as 920 billion tons of CO_2-equivalent worldwide (Aycaguer et al., 2001). In terms of CO_2 sequestration, geologic storage offers "value-added" benefits, such as using CO_2 in enhanced oil recovery (EOR) operations and in enhanced coal-bed methane (ECBM) production.

For geological sequestration, two case studies will be described. The first is geological sequestration with Enhanced Oil Recovery (EOR) and the second is geological sequestration with Enhanced Coalbed Methane (ECBM) recovery.

3.4.1 Enhanced Oil Recovery (EOR)

Geologic CO_2 sequestration with EOR (Enhanced Oil Recovery) is a proven technology (Holloway, 1997). Under supercritical conditions, CO_2 acts as a powerful solvent that can be used to reduce the viscosity of oil, and therefore increase oil recovery (Aycaguer et al., 2001). EOR projects are already on-going in the U.S., such

as in the Permian Basin of Texas. Typically, the source of CO_2 for this type of project is transported by pipeline from natural CO_2 reservoirs in Colorado, New Mexico and Wyoming (Klara et al., 2003).

EOR is yet to be applied where the source of CO_2 is from electricity generation (Heddle et al., 2003). A Norwegian case study proposes to do this. In the case study, CO_2 is first captured from the flue gas of existing coal-fired power system and sequestered geologically in conjunction with EOR in the North Sea (Agustsson et al., 2004; Solli, 2005). A pipeline, 682 km in length, is used to deliver supercritical CO_2 from a coal-fired power plant to the Gullfaks oil field. For this case, it was convinced that steel pipe engineering technology exists to allow the long-distance pipeline to be produced for CO_2 transportation (Skovholt, 1993; Svensson et al., 2003).

In the proposed CO_2-EOR project, the energy requirement for long distance pipeline transportation is estimated to be 130 kWh/ton, and recompression and injection, 7-9 kWh/ton (Heddle et al., 2003; Solli, 2005). Stevens et al. (2000) estimated that for current EOR projects, up to 10% of CO_2 injected is released to the atmosphere. The entire process results in two benefits: the underground storage of CO_2, and the extraction of a useful resource, oil. The recovery of oil is taken to be 0.18 ton of oil for every ton CO_2 sequestered (Aycaguer et al., 2001), and the oil recovery process itself requires approximately 94 kWh/ton of oil recovered (Heddle et al., 2003).

One of the main credits for this type of project is the recovery of oil.

3.4.2 Enhanced Coalbed Methane (ECBM) Recovery

Another attractive option for disposal of CO_2 is sequestration in deep, unmineable coal seams. Deep unmineable coal formations provide an opportunity to both sequester anthropogenic CO_2 and at the same time increase the production of methane or natural gas. In this type of method, the adsorption of CO_2 causes the desorption of the gas. Accordingly, enhanced coalbed methane (ECBM) recovery is a promising technology for mitigating greenhouse gas emissions from coal-fired power plants and while providing significant economic benefit (Klara et al., 2003).

The ECBM case study is taken from Tamabayashi at al. (2004), where the Chikuhou coalfield in Kyushu, Japan, is identified to be a potential area for coalseam CO_2 sequestration. After CO_2 recovery, the gas is transported by pipeline to the injection site. During the injection of CO_2, methane or natural gas is recovered. It was estimated that compression and pipeline transportation requires 100 kWh/ton CO_2 and injection requires 5-6 kWh/ton (Sagisaka, 2005). These data agree closely with those reported for ECBM studies performed in the U.S. (Heddle et al., 2003).

The production of natural gas requires approximately 38 kWh/ton (Heddle et al., 2003). The average ratio of CO_2-to-gas recovery is taken as 3:1 (Reeves, 2003). This is the amount estimated after taking into account the loss of methane gas (leakage to air). It is also assumed that the methane gas recovered is of acceptable purity and no further processing (separation) is required.

Coals have the ability to physically adsorb large volumes of CO_2 in a highly concentrated state. The leakage rate which is considered “safe and acceptable” for the

underground storage of CO_2 was estimated by von Goerne (2004) as 0.01% per year. According to this estimate, a total 5% CO_2 leakage is expected for a 500-year period.

The concepts for both geological sequestrations with EOR/ECBM applications are illustrated in Figure 3.11.

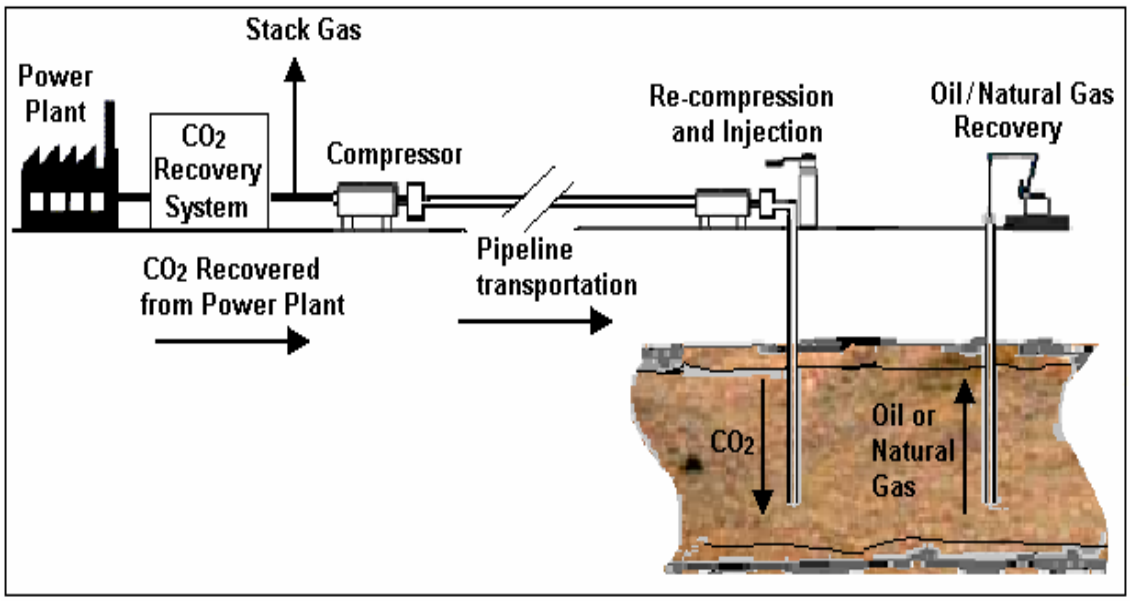


Figure 3.11. Geological sequestrations of CO_2 with EOR/ECBM applications

3.5 Mineral Sequestration

An alternative sequestration route is the so-called mineral CO_2 sequestration route in which CO_2 is chemically stored in solid carbonates by the carbonation of minerals (Goldberg et al., 2001). The basic principle of mineral CO_2 sequestration is the acceleration of naturally occurring weathering process to form stable carbonate rocks. This so-called mineral CO_2 sequestration option or mineral carbonation, was originally proposed by Seifritz (Seifritz, 1990). In this process, magnesium-rich or calcium-rich minerals, such as olivine (Mg_2SiO_4), wollastonite ($CaSiO_3$) or serpentine

($Mg_2Si_2O_5(OH)_4$) react with CO_2 to form geologically stable mineral carbonates, such as $MgCO_3$.

The theorized reaction equation, is shown below (Zevenhoven and Kohlman, 2001):

$$(Mg, Ca)\ x\ SiyOx + 2y + xCO_2\ x(Mg, Ca)\ CO_3 + ySiO_2$$

The main advantage of mineral CO_2 sequestration is the thermodynamic stability of the formed carbonates, which are permanent and inherently safe. The formed mineral carbonates are claimed to be stable over geological time periods (millions of years) (Voormeij and Simandl, 2003). Another advantage is the vast natural abundance of the required minerals (Goldberg et al., 2001).

Mineral CO_2 sequestration is a new concept and is less studied compared to other types of sequestration options (Park et al., 2003). There is presently no mineral sequestration plant in operation (Goldberg and Walters, 2002).

3.5.1 Mineral Sequestration Case Study

The case study is taken from O'Connor et al. (2005). The research team from the Albany Research Center has carried out various experiments for mineral carbonation as a potential option for CO_2 sequestration. From the series of experiments conducted by the team, five process methods are selected for comparison. Research studies concerning the chemical reactions and thermodynamics of the mineral carbonation processes have been carried out by a various researchers (e.g., O'Connor et al., 2005; Lackner, 2002; Zevehoven and Kohlman, 2001). Therefore this project will not cover these aspects and will focus instead on a different perspective of CO_2 mineral

sequestration – emissions and pollution due to energy consumed for each process. Five methods will be presented for CO_2 storage in the form of stable mineral rocks. The selected minerals and process routes or methods – taken from the Albany Research Center, U.S. Department of Energy – are as follows (O'Connor et al., 2005):

- **Method 1**: olivine, 100% grade
- **Method 2**: olivine, 70% grade
- **Method 3:** serpentine (Lizardite), 100% grade
- **Method 4**: serpentine (Antigorite), 100% grade
- **Method 5**: Wollastonite, 50% grade

The flow diagram – illustrating the process routes for all the selected methods (1-5) – is displayed in Figure 3.12.

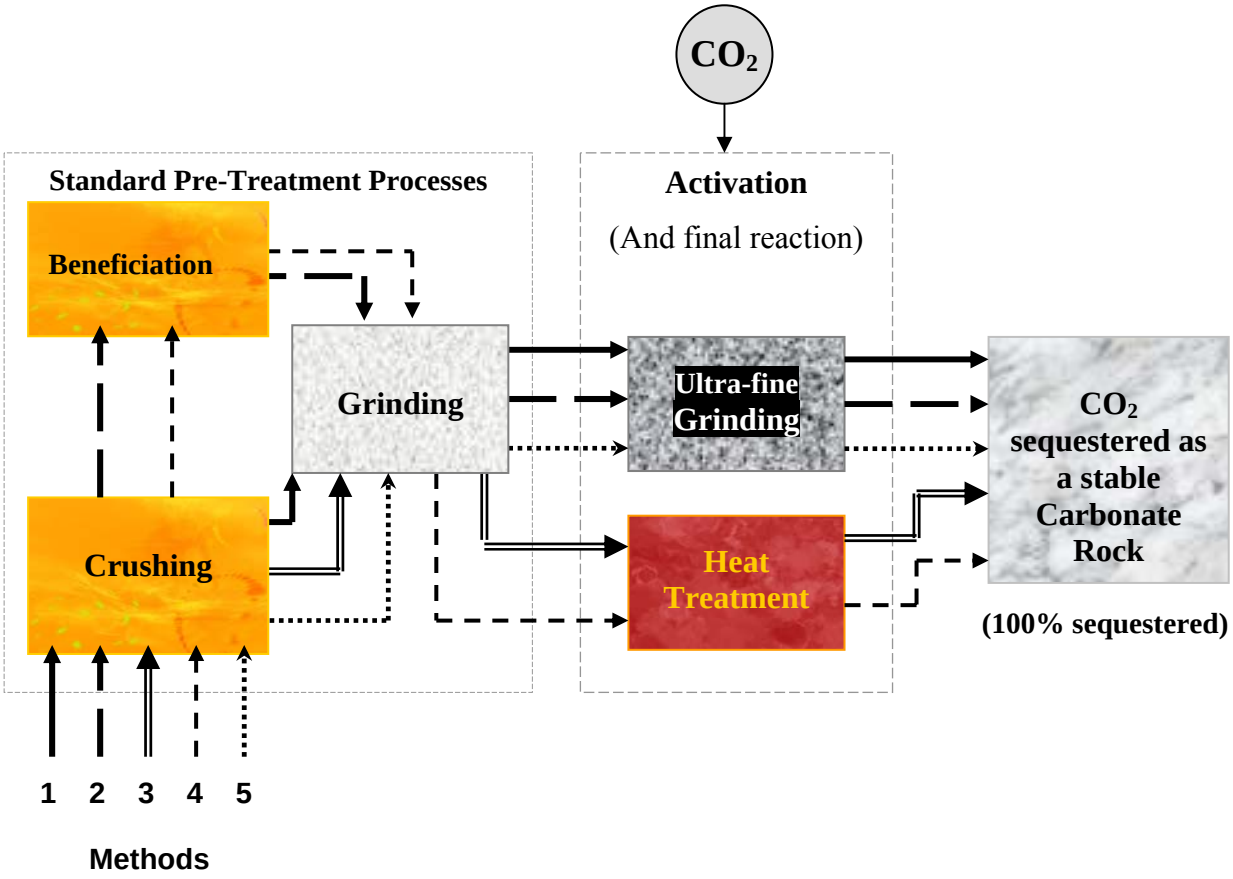


Figure 3.12. Process Routes for five for CO_2 mineral sequestration methods

As shown in Figure 3.12, the mineral sequestration process methods start with the various minerals (different grades of olivine, serpentine and wollastonite), the crushing of these materials and next, beneficiation (for methods 2 and 4) before the final "Activation" stage. The crushing energy required for all minerals is estimated to be 2 kWh per ton mineral; and the benefication process, 2-4 kWh per ton of mineral (O'Connor et al., 2005). The mining and excavation of minerals are not included in the LCA system boundary.

The amount of mineral required to react with CO_2 differs with various types of rocks. For example, approximately 2 tons of serpentine is required to react with 1 ton of CO_2. These values, designated as Rco_2, were reported by various literatures (e.g., O'Connor et al., 2004; Park et al., 2003; Zevenhoven and Kohlmann, 2001). The conversion efficiency of each mineral is known as Rx. The Rx values are highly dependant on mineral pre-treatment processes, which are described in the report provided by O'Connor et al. (2005). Mineral reactivity is enhanced by the "activation" process which can be carried out by ultra-fine grinding (for olivine and wollastonite) or heat treatment (for serpentine). For ultra-fine grinding, an energy penalty of 70 – 150 kWh per ton of mineral is incurred, and for heat treatment, roughly 300 kWh/ton of serpentine mineral (O'Connor et al., 2004).

The final outcome of the system is a stable mineral product, known as a carbonate rock, where CO_2 is stored indefinitely. One of the suggested industrial applications for the carbonate product is as a construction material.

This project will perform a complete LCA investigation on the four CO_2 recovery technologies combined with the various CO_2 sequestration options. The details of the LCA goal and scope, system boundaries and data and assumptions will be described in the next chapter.

CHAPTER 4

LCA Evaluation of CO_2 Recovery and Sequestration

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4.1 LCA Research Methodology

This project is the first to investigate all the stages involved in CO_2 recovery and sequestration, thereby linking the "CO_2 route" – from its source (power plant flue gas) to its final destination (storage area). The use of materials for construction and making of equipments (hanging platform, pipes, tankers, etc) are not included in the LCA study. The research steps will be carried out according to: i) ISO 14041: Goal and Scope Definition and Inventory Analysis, ii) ISO 14042: Life Cycle Impact Assessment and iii) ISO 14043: Interpretation.

4.2 Goal, Scope & Inventory Analysis (ISO 14041)

The overall methodology and Main System Boundary is illustrated in Figure 4.1. The **Functional Unit** is selected as the generation of **1 MWh** from the power plant. This system boundary defines the **scope** of the LCA investigation. Within this scope, the overall LCA **goal** is to:

- First study the sub-systems individually and separately – as Stages 1, 2 and 3 – and compile their relevant life cycle inventory (LCI) data
- Next, calculate the potential environmental consequences of each stage involved. Suitable and highly recognized impact assessment methods will be employed to do this

- And finally, evaluate the overall impact assessment results of all three stages (treated as a continuous chain of processes). In the final evaluation, the final scores will be generated and sensitivity analysis will also be carried out.

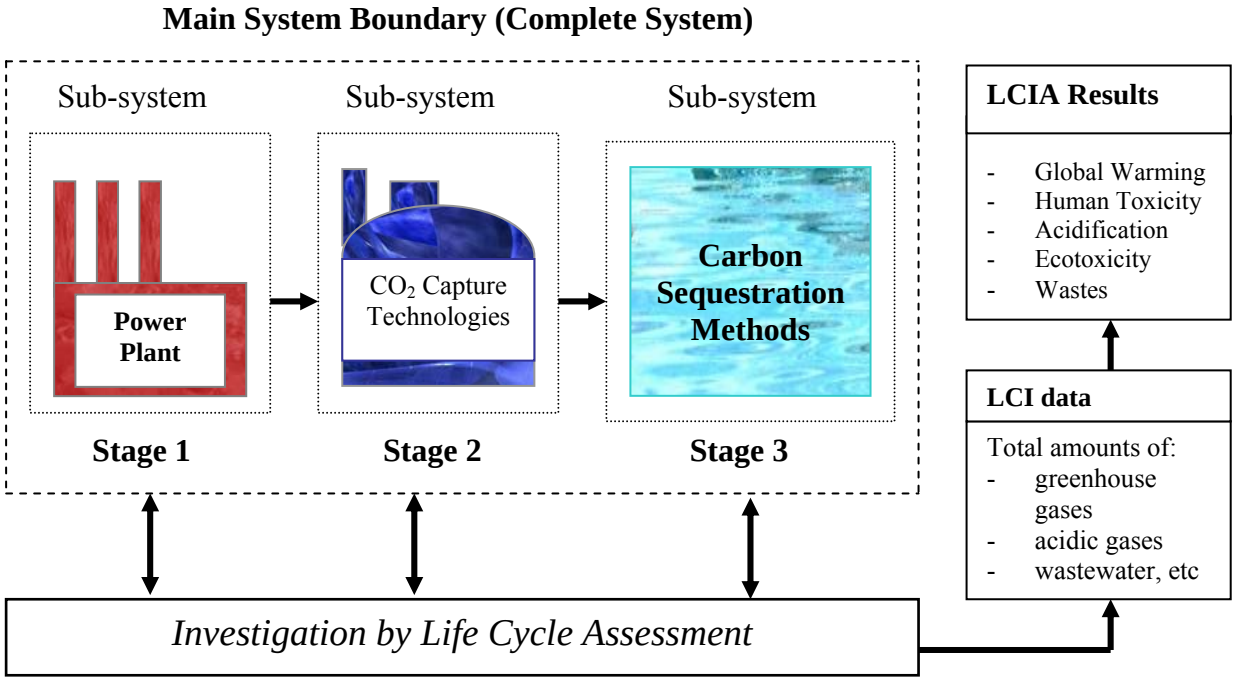

Figure 4.1. Main System Boundary

From here onwards, the coal-fired power plant, CO_2 recovery technologies and sequestration systems are designated as:

Stage 1: Coal-fired power plant

Stage 2: CO_2 recovery (post-combustion) technologies

Stage 3: CO_2 Sequestration (ocean, geological, mineral)

Stage 1 starts with coal mining and ends with the final amount of electricity produced (selected to be **1 MWh**) as the end product. Stage 2 begins with the amount of CO_2 emissions entering the system, due to electricity production from the power plant, and

ends with the final amount of CO_2 recovered. Stage 3 begins with the emissions of CO_2 entering the system and ends with the final amount of CO_2 sequestered.

The next sub-sections provide details of the three individual systems, data requirements and assumptions.

4.2.1 System Boundary 1 & Inventory Data 1

The system boundary (sub-system) for the Stage 1 is shown in Figure 4.2.

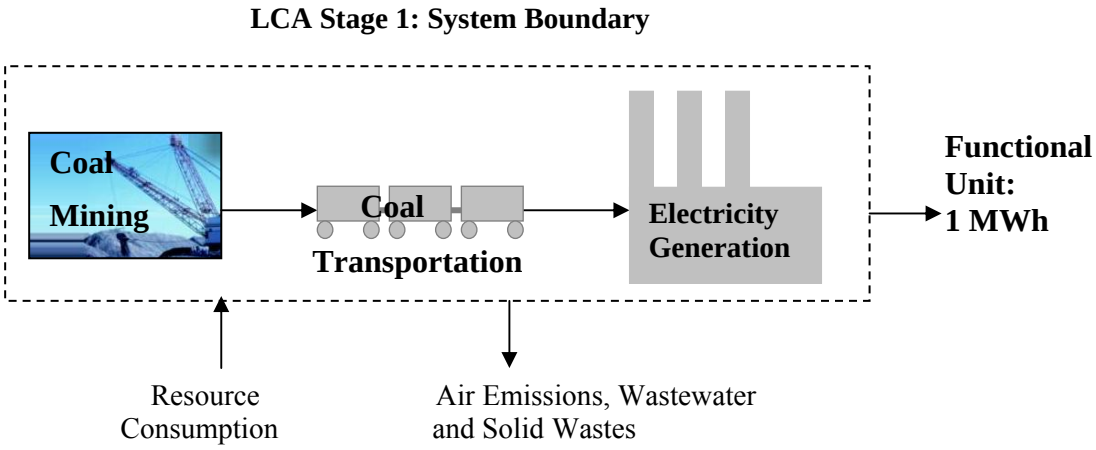

Figure 4.2. LCA system boundary for coal-fired electricity generation (Stage 1)

4.2.1.1 Inventory data 1, estimations and assumptions

Due to the size and complexity of the project, the inventory data will focus on:

- Resources consumed for coal mining, transportation and electricity generation
- Wastes from coal mining, transportation and electricity generation
- Main air emissions from coal mining, transportation and electricity generation
- Water emissions from coal mining and electricity generation.

The LCI data for the coal-fired power generation was obtained from three coal-fired power plants operating in U.S. by the National Renewable Energy Laboratory. All three power plant systems examined incorporate pulverized coal boilers. The collection of emissions from the plants was conducted annually, taking into account each emission in the year it occurs. In order to obtain this information, a separate inventory of the system was conducted for a total of 32 times. This was done for each of the three power plant's operating system, resulting in a total of 96 separate analyses (Spath et al., 1999).

The LCI results for LCA Stage 1 are tabulated in Tables 4.1-4.4. The energy requirements for mining, transportation and electricity generation are expressed in terms of the amounts of coal, natural gas and oil.

Table 4.1. Main resources (energy requirements) for the generation of 1 MWh

Main Resources (kg)	Coal mining	Transportation	Electricity generation
Coal	3.57E+00	4.76E-02	4.72E+02
Natural gas	4.82E-01	2.15E-02	7.47E-01
Oil	3.24E-01	5.53E+00	5.64E+00

Table 4.2. Main air emissions due to the generation of 1 MWh

Main Air Emissions (kg)	Coal mining	Transportation	Electricity generation
CO_2	9.59E+00	1.75E+01	9.50E+02
CO	9.21E-03	1.01E-01	1.56E-01
CH_4	9.04E-01	9.13E-04	8.49E-03
N_2O	1.00E-03	2.46E-04	3.18E-03
SOx	7.10E-02	9.51E-02	6.53E+00
NOx	4.76E-02	1.85E-01	3.12E+00
NH_3	9.86E-02	9.88E-05	1.09E-04
PM	1.29E-02	1.84E-02	9.18E+00
VOCs	8.13E-02	5.89E-02	7.28E-02
HCl	5.49E-09	5.84E-08	1.77E-06
HF	9.71E-09	7.34E-09	1.53E-07
H_2S	2.79E-09	3.07E-10	8.90E-09

Table 4.3. Heavy metal emissions due to the generation of 1 MWh

Heavy metal Emissions (g)	Coal mining	Transportation	Electricity generation
Antimony	0	0	4.10E-03
Arsenic	0	0	4.95E-02
Barium	0	0	1.30E-02
Beryllium	0	0	1.60E-03
Boron	0	0	1.70E+01
Cadmium	0	0	4.10E-03
Chromium	0	0	5.92E-02
Cobalt	0	0	6.90E-03
Copper	0	0	2.34E-02
Lead	0	0	3.00E-02
Manganese	0	0	4.30E-03
Mercury	0	0	3.66E-02
Molybdenum	0	0	3.81E-02
Nickel	0	0	5.79E-02
Selenium	0	0	4.06E-01
Vanadium	0	0	8.80E-02

Table 4.4. Wastewater discharge due to the generation of 1 MWh

Water Emissions (kg)	Coal mining	Transportation	Electricity generation
Acids (H^+)	2.56E-05	2.57E-09	8.22E-08
Ammonia	2.53E-02	0.000003229	1.5E-08
BOD	5.34E-04	3.06E-05	3.13E-05
COD	1.61E-03	9.16E-05	9.31E-05
Chlorides (Cl^-)	9.80E-08	1.63E-07	3.18E-06
Cyanides (CN^-)	2.26E-09	1.90E-10	6.10E-09
Fluorides (F^-)	6.93E-06	3.20E-08	1.05E-06
Metals	8.35E-08	9.58E-09	2.74E-07
Nitrates ($NO3^-$)	1.57E-06	1.46E-09	5.10E-08
Oils	8.58E-05	8.32E-04	9.32E-04
Phenol	7.06E-09	6.00E-10	1.91E-08
Sodium (Na^+)	1.09E-06	2.39E-08	4.79E-07
Sulfates ($SO4^-$)	1.40E-06	2.31E-08	4.67E-07
Sulfides (S^-)	4.53E-09	3.80E-10	1.22E-08
Suspended matter	5.50E-05	3.23E-05	1.43E-04

With the implementation of an LEBS (Low Emission Boiler System) for the power plant, the total solid waste from mining, transportation and electricity generation is estimated to be 20.7 kg for every generation of 1 MWh (Spath et al., 1999).

4.2.2 System Boundary 2 & Inventory Data 2

Stage 2 involves four CO_2 recovery systems: chemical absorption, membrane separation, cryogenics and pressure swing adsorption (PSA). The system boundary for LCA Stage 2 is displayed in Figure 4.3. It starts electricity generation, next, CO_2 entering the system and ends with the recovered CO_2 gas.

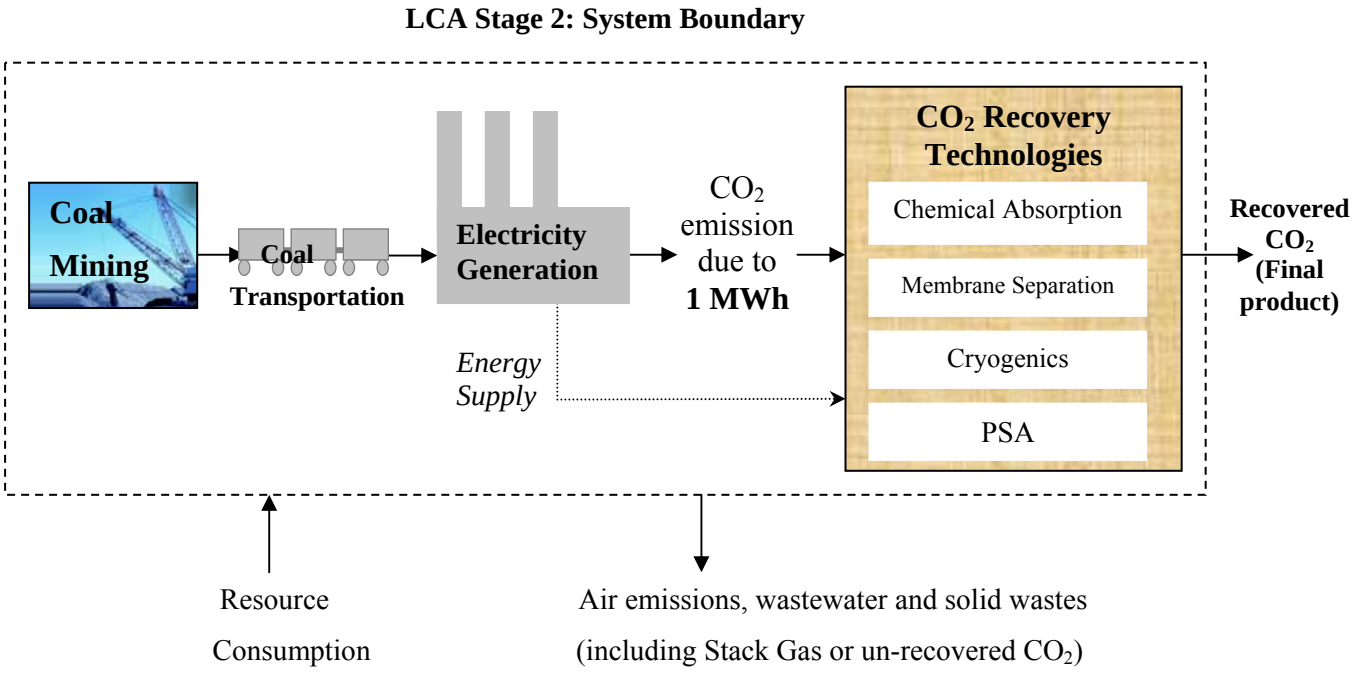

Figure 4.3. System Boundary for LCA Stage 2

4.2.2.1 Inventory data 2, estimations and assumptions

As primary data for the post-combustion technologies are unavailable, the energy estimations and recovery efficiencies have been extracted from reports and personal communications with scientists who are familiar with CO_2 recovery processes (e.g., Bolland, 2005; Gielen, 2003; Audus, 2000; Göttlicher and Pruschek, 1997). These data are compiled in Table 4.5.

Table 4.5. Data used for LCA Stage 2

CO_2 Removal Technology	Energy requirement in kWh/ton (lower & upper limits)	Percentage capture (lower & upper limits)	End product
Chemical Absorption	330 340	95% 98%	Condensed CO_2
Membrane Separation	70 75	82% 88%	CO_2 gas
Cryogenics	600 660	90% 95%	Liquid CO_2
Pressure Swing Adsorption (PSA)	160 180	85% 90%	CO_2 Gas

It is noted that for Table 4.5, the reported CO_2 capture efficiencies are based on rather ideal plant operating settings. Lower efficiencies may be realized in an actual plant where the running conditions are below expectations. However, for the objective of performing a comparison between the four technologies, these data will be used.

4.2.3 System Boundary 3 and Inventory Data 3

In the final stage, LCA is carried out to investigate the following: case studies of five ocean sequestration options, two geological sequestration methods and five mineral sequestration alternatives. The system boundary for Stage 3 is shown in Figure 4.4. In the system boundary, the sequestration systems are regarded as "stand alone" operations, where the sequestration activities are assumed to be carried out in the absence of any CO_2 recovery technologies in place.

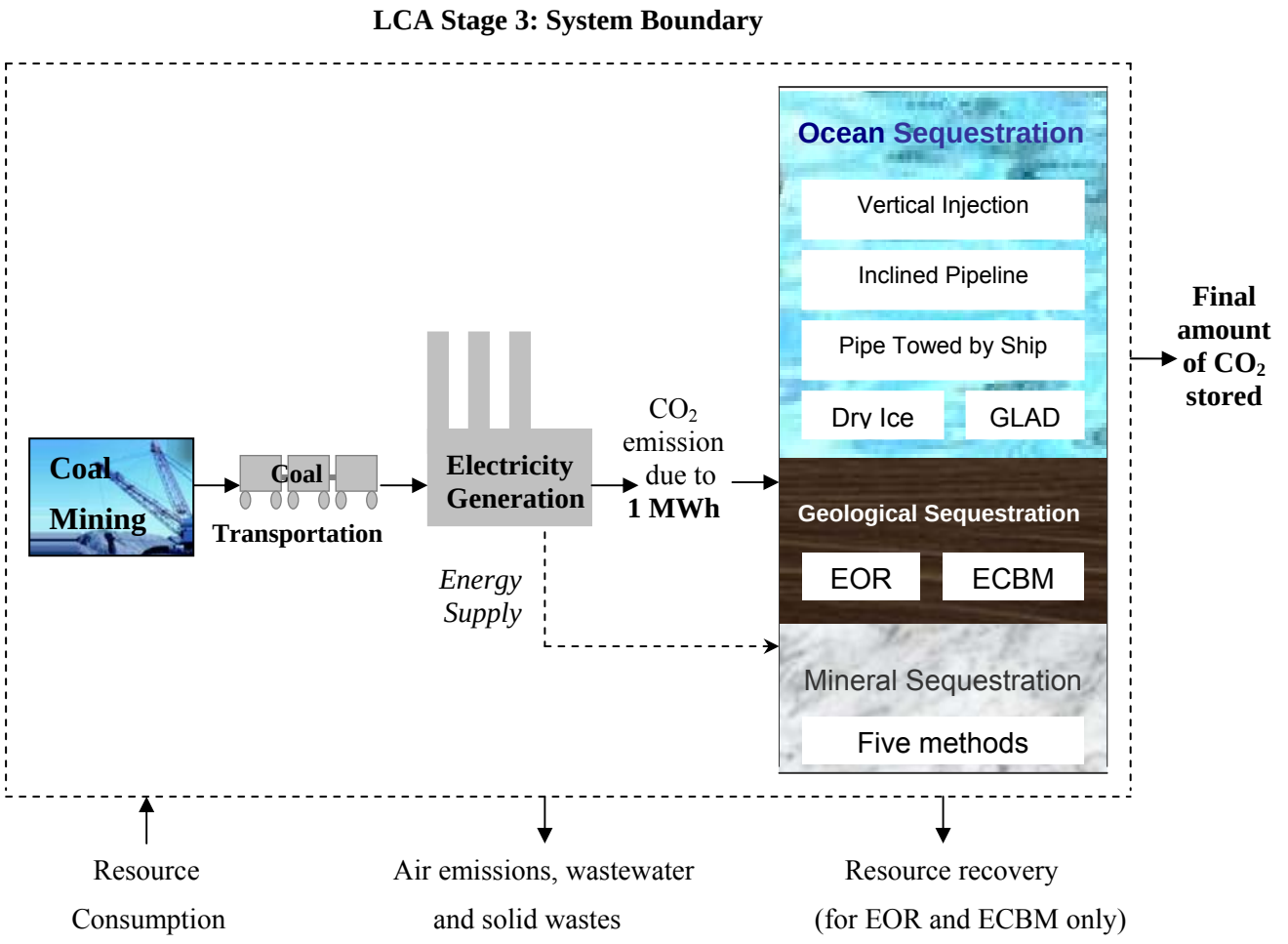

Figure 4.4. System Boundary for LCA study of Stage 3

4.2.3.1 Inventory data, estimations and assumptions: Ocean and Geological Sequestration

Also for Stage 3, primary data for the sequestration methods are yet to be publicly available; the energy values estimated for CO_2 pipeline transportation, compression, injection, liquefaction, sublimation and fossil fuel recovery (for geological sequestration) have been extracted from the latest reports, as well as from personal communications with other researchers who are involved in similar types of CO_2 sequestration studies (e.g., Sagisaka, 2005; Solli, 2005; Niwa, 2004; Agustsson and Statoil, 2004; Heddle et al., 2003).

Apart from the energy estimations, the final percentage of CO_2 sequestered will be based on literature findings (von Goerne, 2004; Herzog et al., 2001; Stevens et al., 2000). The set of data used for both ocean and geological sequestration are displayed in Table 4.6.

In an ideal investigation, the LCIA should include the adverse impacts on marine life due to the "dumping" of CO_2 in the ocean. However, this particular environmental impact category is yet to be developed in the EDIP impact assessment method. Therefore the impact of marine life or any other types of benthic lifeforms due to the increase of CO_2 concentrations in the ocean are not included in the LCA investigation.

4.2.3.2 Inventory data, estimations and assumptions: Mineral Sequestration

The types of mineral used for each mineral sequestration method (1-5) and the respective energy consumed from crushing, benefication, grinding and heat treatment are extracted from O'Connor et al. (2005). These data, reported as kWh per ton mineral, are presented in Table 4.7.

The Rco_2 values and Rx of the respective cases, as well as the total Standard Pre-Treatment and Activation energy requirements are compiled in Table 4.8, based on kWh per ton CO_2 sequestered. All data are taken from O'Connor et al. (2005), except for the Activation energy requirements, which are derived from Lyons et al (2003). Personal communications with the research scientists involved in the mineral sequestration experiments were made to ensure that the LCI used for the comparisons are justifiable and consistent for all cases (e.g., O'Connor, 2005; Dahlin, 2005).

Table 4.6. Data used for LCA Stage 3 (Ocean and Geological Sequestration)

CO_2 Sequestration Options	**Brief Description**	**Total Energy demands in kWh/ton** (For liquefaction, compression, injection, resource recovery, etc.)	**Percentage sequestered**
Ocean Sequestration: Vertical Injection	Transportation of liquid CO_2 by ocean tanker; final injection by vertical pipe from floating platform	Liquefaction = 120 Compression & injection = 45	90%
Ocean Sequestration: Inclined pipe	Pipeline transportation of compressed CO_2, followed by re-compression & injection	Compression for pipeline transportation = 100 Re-compression & injection = 35	81%
Ocean sequestration: Pipe Towed by Ship	Transportation of liquid CO_2 by ocean tanker; final injection from Pipe Towed by Ship	Liquefaction = 120 Compression & injection = 27.5	74%
Ocean Sequestration: Dry Ice	Ocean tanker carrying solid CO_2, final disposal of Dry Ice	Sublimation process = 240	90%
Ocean Sequestration: GLAD	GLAD system (dissolution of CO_2 in gaseous form)	GLAD system = 3.7	74%
Geological Sequestration: with EOR	Pipeline transportation of compressed CO_2; re-compression & injection of CO_2 into underground media; recovery of oil	Long distance pipeline transportation + injection = 138 Oil recovery = 94	90%
Geological Sequestration: with ECBM	Pipeline transportation of compressed CO_2; re-compression & injection of CO_2 into underground media; recovery of natural gas	Long distance pipeline transportation + injection = 106 Oil recovery = 38	95%

Table 4.7. Data for Mineral Sequestration based on kWh/ton mineral

Method	Type of Mineral	Standard Pretreatment and Carbonation (kWh/ton mineral)		Activation (kWh/ton mineral)	
		Crushing and Benefication	Grinding Processes	Ultra-fine Grinding	Heat Treatment
1	Olivine, 100%	2	81	150	-
2	Olivine, 70%	4	85	150	-
3	Serpentine, 100% (Lizardite)	2	11	-	326
4	Serpentine, 100% (Antigorite)	2	81	-	293
5	Wollastonite, 50%	6	91	70	-

Table 4.8. Data for Mineral Sequestration based on kWh/ton CO_2 sequestered

Method	Tons of mineral required (R_{CO2})	Conversion Efficiency (Rx)	For the sequestration of 1 ton of CO2		
			Total Energy for Standard Pre-Treatment and Carbonation (kWh/ton CO2)	Total Energy for Activation: Heat Treatment (kWh/ton CO2)	Total Energy for Activation: 3rd Stage Grinding (kWh/ton CO2)
1	1.8	0.81	300	333	-
2	1.8	0.81	320	333	-
3	2.5	0.40	180	-	2022
4	2.1	0.92	180	-	829
5	2.8	0.82	190	239	-

For each case, 100% of the CO_2 is sequestered (no leakage). It is also assumed for all five cases that the power plant is situated right next to the mineral sequestration system, therefore the transportation of CO_2 is not required (Dahlin, 2005).

4.3 Impact Assessment and Interpretations (ISO 14042 & 14043)

The EDIP impact assessment method will be applied to calculate the potential environmental consequences of the four CO_2 recovery technologies and a total of 12 CO_2 sequestration options. The eight important impact categories selected are: Global Warming Potential, Acidification, Human Toxicity to Air, Human Toxicity to Water, Eutrophication, Ecotoxicity, Wastes and Resources. These impact assessment categories are selected based on their relevance to the LCI data generated. Acidic gases contribute to both Acidification and Smog formation. Between the two impact categories, Acidification was selected due to the higher severity of the environmental problems associated with it (Larssen and Holme, 2006; Curtis et al., 2005). Other impact categories, such as, Ozone Depletion and Radiation are not included because no ozone depleting pollutants or radiation substances were reported for the LCI.

For Stage 3, the first round of impact assessment results are calculated based on the sequestration systems alone, without taking into account any pollution generated from CO_2 recovery processes.

Chapter 5 will present the first round of results. In chapter 6, further results and interpretations will be made for the Main System's (complete system) **final scores**, **sensitivity analysis** and **sequestration effectiveness**.

A detailed step by step calculation for the LCIA (e.g., GWP) is illustrated in **APPENDIX B.**

CHAPTER 5

Results and Discussions

CHAPTER 5

Results and Discussions

5.1 Life Cycle Impact Assessment Results

For the all the results presented, the amount of CO_2 generated from the coal-fired power plant is taken to be 950kg per MWh. The *lower limits* of the post-combustion energy demands are used as the criteria for the LCIA calculations, along with the CO_2 removal efficiencies of: 95% for chemical absorption, 82% for membrane separation, 90% for cryogenics and 85% for pressure swing adsorption. For all Acidification impact categories, the results were calculated according to the regulation of 90% removal of SOx and NOx from the coal-fired power plant (USEPA, 2003). Also for Human Toxicity to Air impact categories, all the results were generated after the regulation of the removal of 95% of heavy metals from the power plant flue gas (Offen, 2003).

5.2 CO_2 Recovery results

With the EDIP impact assessment method, the results for Global Warming Potential, Acidification, Human Toxicity to Air, Human Toxicity to Water, Eutrophication, Ecotoxicity, Wastes and Resources for the four CO_2 recovery technologies are displayed in Figures 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8 respectively.

5.2.1 Global Warming Potential

The first results (Figure 5.1) compare the Global Warming Potential (GWP) among the four CO_2 recovery methods. It can be observed that the most promising system

for CO_2 post-combustion recovery stem from the highest efficiency of the greenhouse gas that can be captured from the power plant, combined with reasonable energy demands. In this case, chemical absorption using MEA, followed by PSA. Although Cryogenics technology is capable of recovering a large amount (90%) of CO_2 from the power plant, its large energy consumption (600 kWh/ton CO_2 recovered) resulted in additional greenhouse gas emissions. However, an incentive for cryogenic fractionation is that CO_2 can be recovered in liquid form. This means that for combined systems of Vertical Injection and Pipe Towed By Ship (ocean sequestration methods) with cryogenics, the CO_2 liquefaction process that is required for ocean tanker transportation may be omitted.

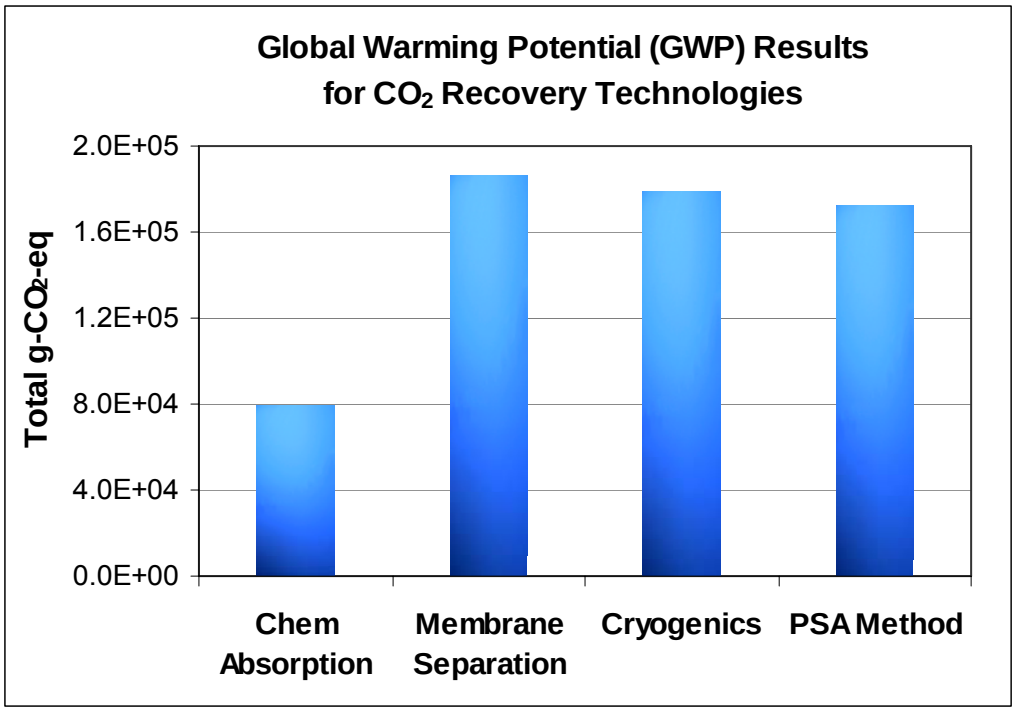

Figure 5.1. Global Warming Potential results for CO_2 Recovery Technologies

The membrane separation technology displayed slightly higher environmental impact results as compared to PSA and the cryogenics technologies. These are due to the higher amount of CO_2 escaping as stack gases, that is, as much as 18% of un-

recovered CO_2. However, membranes have been widely applied in industry as useful CO_2 recovery systems based on their merits of having simple process designs, lower costs and low energy requirements (Wong and Bioletti, 2002).

5.2.2 Acidification

For the Acidification impact category, SO_2 and its potential for acid formation is suggested as the reference substance. The environmental impact results for Acidification is displayed in Figure 5.2.

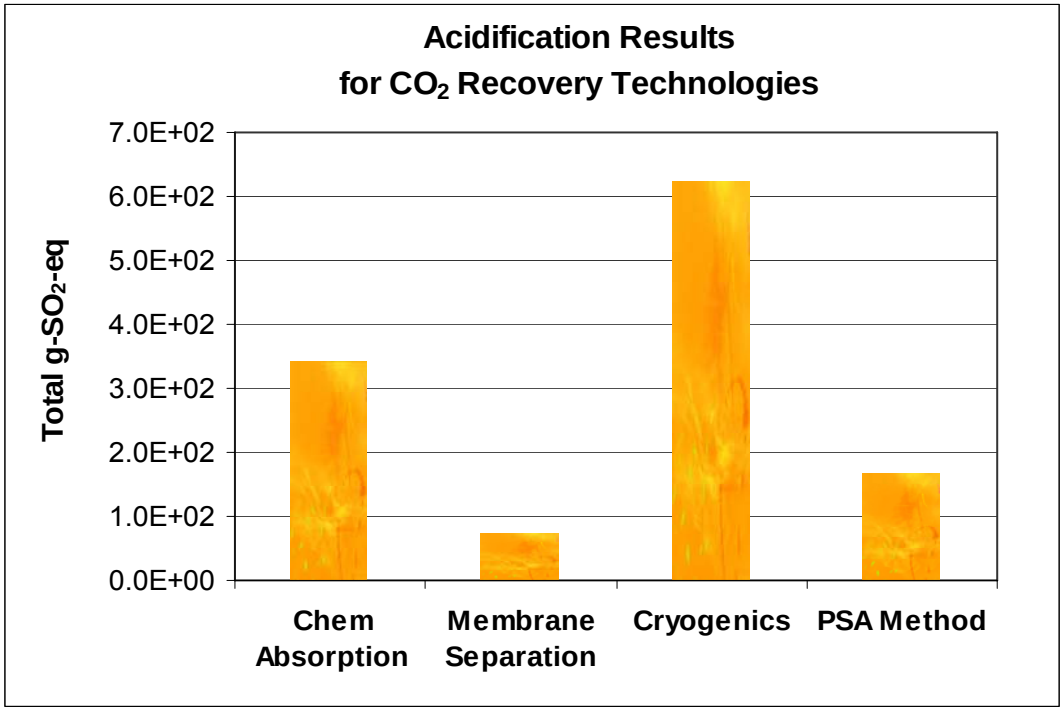

Figure 5.2. Acidification results for CO_2 Recovery Technologies

The highest contributions to Acidification are cryogenics, and next chemical absorption, followed by PSA. The least environmental impact stems from membrane separation due to the technology's lowest energy consumption (70 kWh/ton CO_2 recovered).

5.2.3 Human Toxicity to Air and Water

Whilst the purpose of the post-combustion technologies is to reduce CO_2 emissions to the atmosphere, there are a series of air and water emissions that comes along with the series of processes involved. Air emissions containing heavy metals such as arsenic, cadmium, lead and mercury contribute to Human Toxicity to Air; and water emissions containing metallic ions and phenol contribute to the Human Toxicity to Water impact category. The results for the two local impacts are displayed in Figures 5.3 and 5.4 respectively.

Both figures display the same trend – higher energy demands for the CO_2 recovery processes results in a proportional increase in electricity supply by the coal-fired power plant. As expected, the membrane separation method demands the least amount of energy required to recover CO_2, and therefore displays the lowest peak.

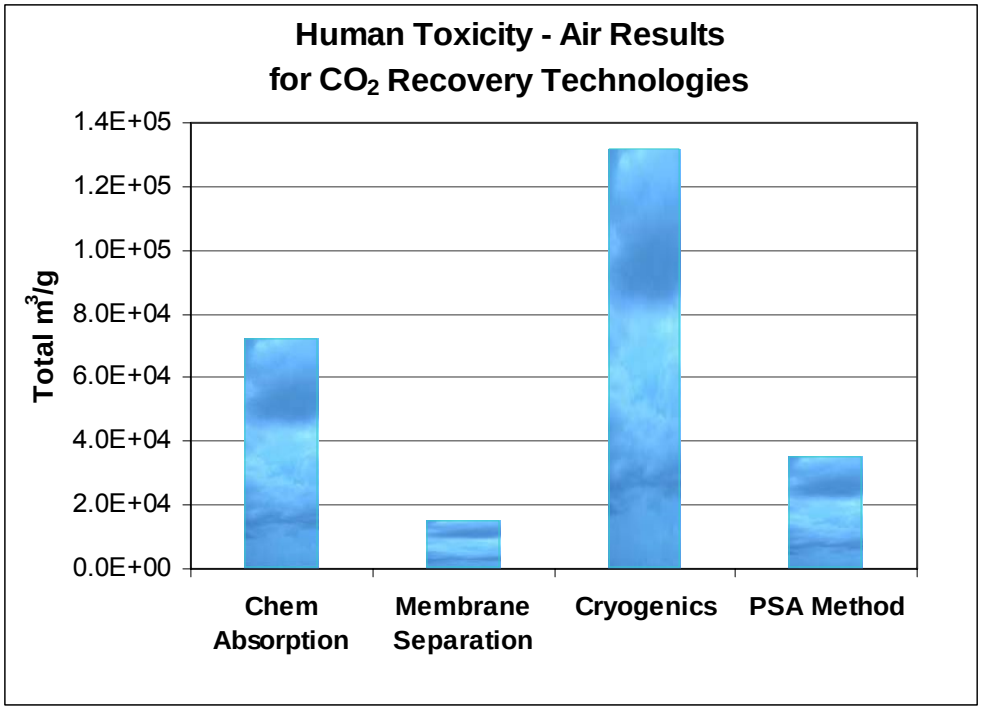

Figure 5.3. Human Toxicity to Air results for CO_2 Recovery Technologies

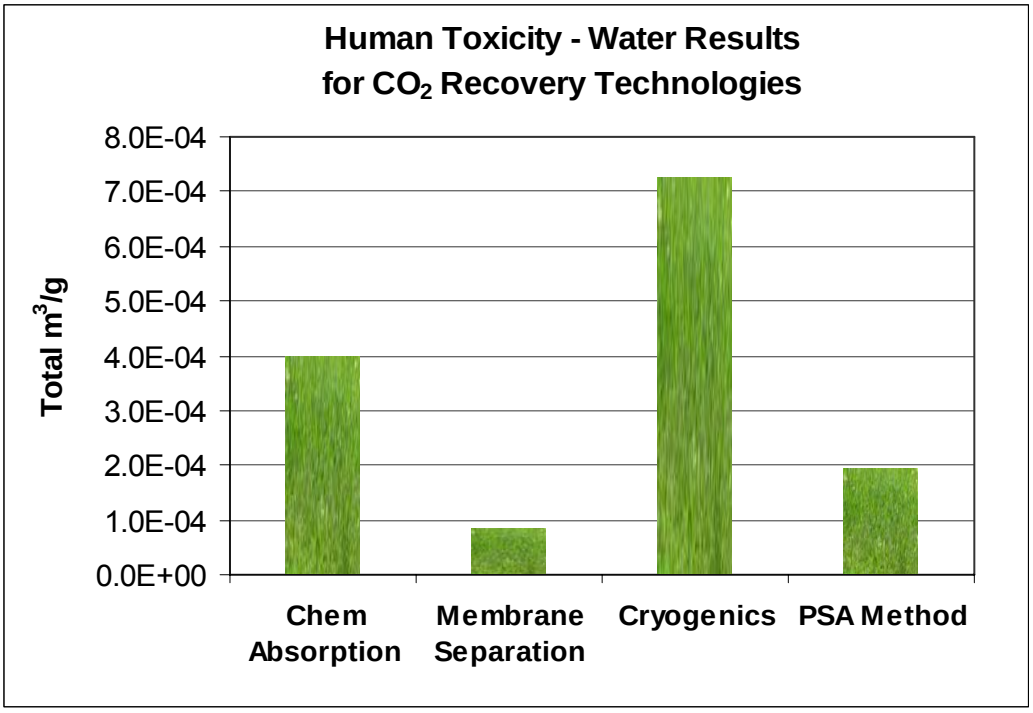

Figure 5.4. Human Toxicity to Water results for CO_2 Recovery Technologies

5.2.4 Eutrophication and Ecotoxicity

Eutrophication is caused by the accumulation of nitrates, ammonia and cyanides, as well as air emissions of N_2O and NOx. Eutrophication, also known as nutrient enrichment, can be considered as a regional as well as local environmental impact. In the EDIP methodology (Hauschild and Wenzel, 1998), the Ecotoxicity impact category is considered in aquatic ecosystems (acute and/or chronic), in terrestrial ecosystems (chronic exposure) and in wastewater treatment plants. Wastewater containing acids and sulfides contributes to Ecotoxicity (water acute).

The results for Eutrophication and Ecotoxicity are displayed in Figures 5.5 and 5.6. Both display the quantified environmental loads that are potentially released into the environment by the employing the four CO_2 recovery systems.

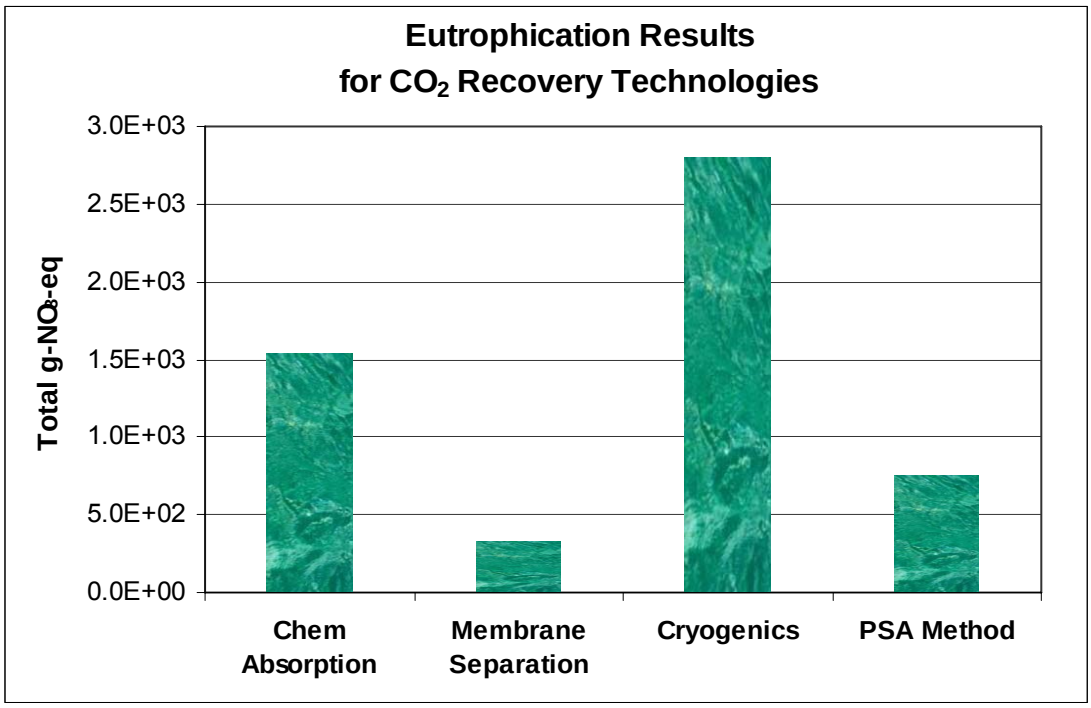

Figure 5.5. Eutrophication results for CO_2 Recovery Technologies

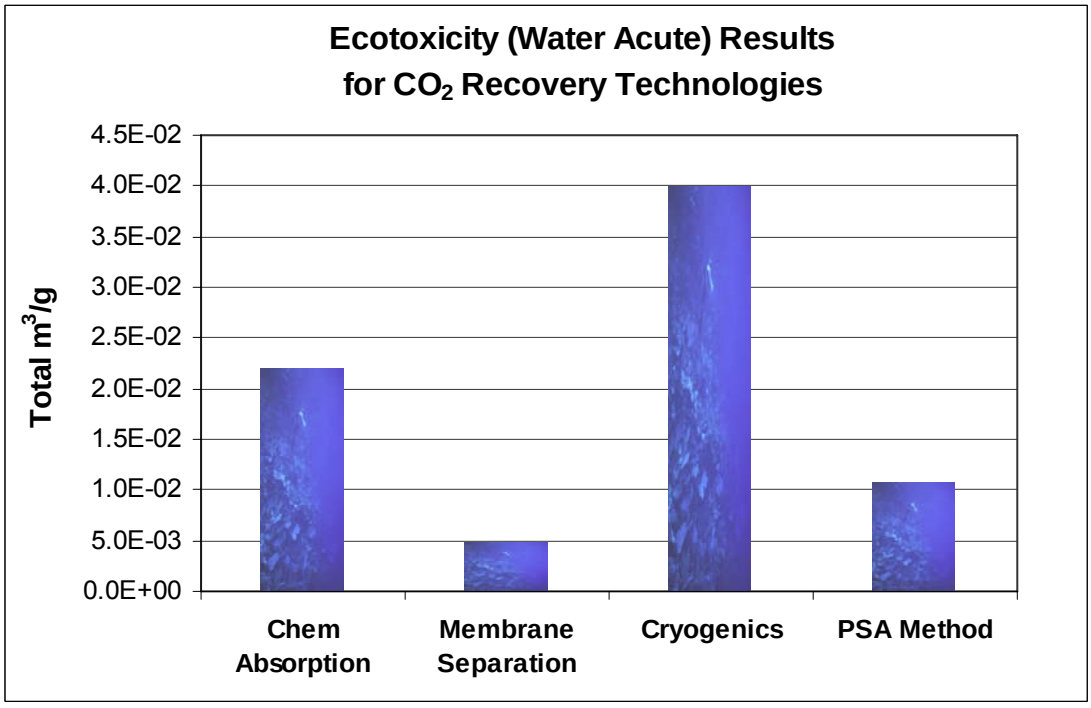

Figure 5.6. Ecotoxicity results for CO_2 Recovery Technologies

5.2.5 Wastes and Resources

One of the biggest environmental concerns of coal-fired power plants is the generation of a significant amount of waste material from the pulverized coal boilers. The solid wastes results due to mining, transportation and final electricity generation are displayed in Figure 5.7.

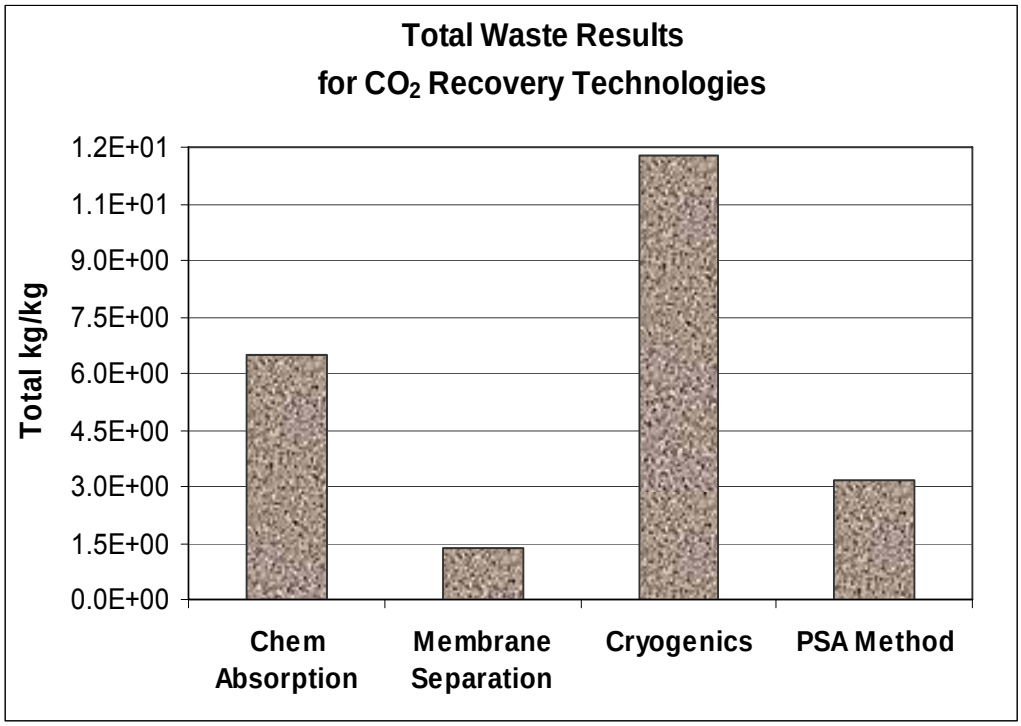

Figure 5.7. Waste results for CO_2 Recovery Technologies

It is very important that the very technologies employed to reduce CO_2 do not themselves create any (more severe) types of environmental burdens. The waste results, displayed in Figure 5.7, have already been significantly reduced by 81%. This reduction is due to the installation of a LEBS (Low Emission Boiler System) in the power plant (Spath et al., 1999). In the near future, all coal-fired power generation technologies will be expected to have a similar type of LEBS equipment in place.

The results for Resources are shown in Figure 5.8. Any types of technology harness energy to work; this requirement is fulfilled by the burning of fuels. The last impact category is predominantly measured by the use of coal, which is projected to remain a dominant source of fuel for electric power generation well into the 21st century (McKee, 2002).

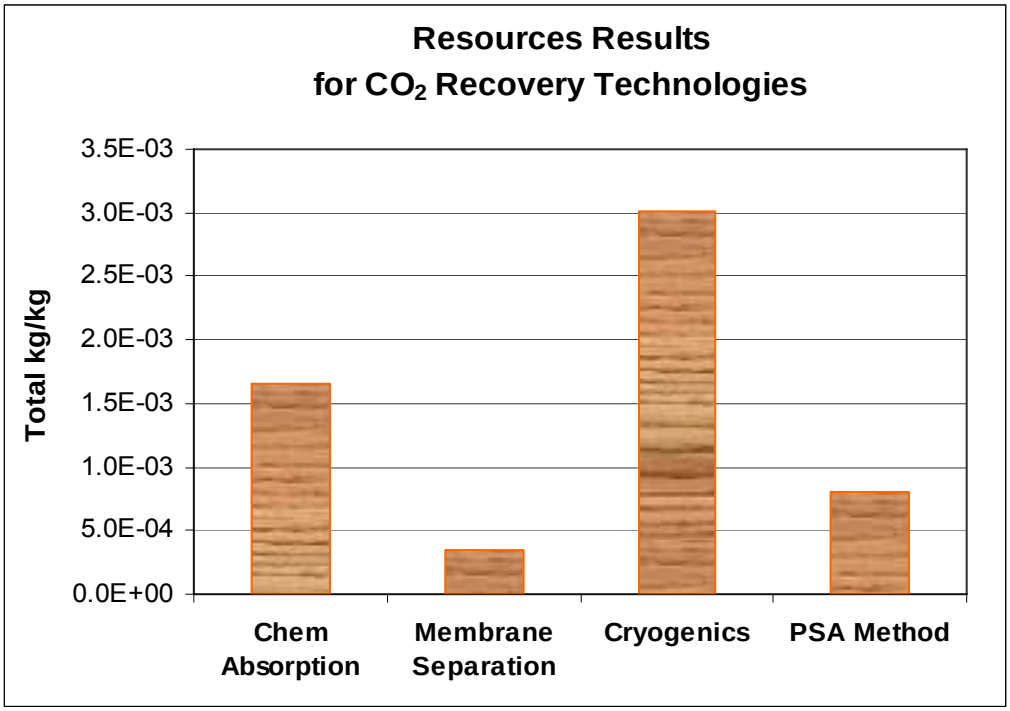

Figure 5.8. Resource results for CO_2 Recovery Technologies

The high energy demands of every processes used to recover each ton of CO_2 – especially for cryogenics (600 kWh/ton CO_2) and chemical absorption (330 kWh/ton CO_2) – is the present impediment to CO_2 separation and recovery for current existing technologies. Driven by the need to reduce greenhouse gases, further developments will be carried out to capture CO_2 effectively, while imposing lighter energy and waste penalties for these types of post combustion recovery systems (Wong and Bioletti, 2002).

5.3 Ocean and Geological Sequestration results

The results for Global Warming Potential, Acidification, Human Toxicity to Air, Human Toxicity to Water, Eutrophication, Ecotoxicity, Wastes and Resources for the ocean and geological sequestration systems are displayed in Figures 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 5.15 and 5.16 respectively.

5.3.1 Global Warming Potential

The GWP result comparing the five CO_2 ocean sequestration options and two geological sequestration systems is displayed in Figure 5.9.

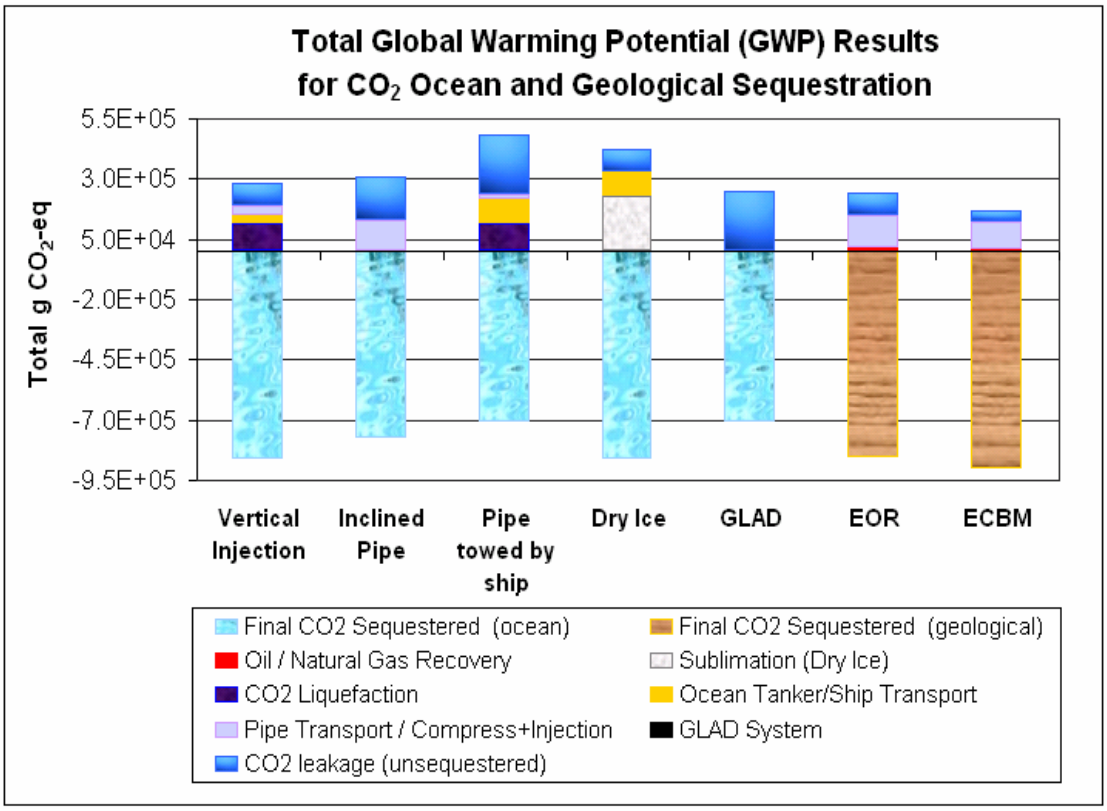

Figure 5.9. Global Warming Potential results for ocean and geological sequestration

Out of all seven cases, geological sequestration with ECBM offers the highest potential amount of CO_2 sequestered, with minimum amounts of greenhouse gases generated from CO_2 compression, pipeline transportation, final injection and natural gas recovery process. A significant amount of global warming prevention (negative peaks), with reasonable environmental impacts (positive peaks) is also displayed by geological sequestration with EOR. The engineering accomplishments for long distance piping, as well as, for pumping or injecting compressed or supercritical gasses into underground reservoirs has been claimed to be a mature and proven field (Svensson et al., 2004; Skovholt, 1993), therefore the notion of storing CO_2 underground may be seen as a feasible and approachable concept.

For ocean sequestration, Vertical Injection appears to be the most promising option in terms of both the final amount of CO_2 stored and reasonable amount of energy spent in the sequestration process. Dry Ice also offers a high percentage of the final storage of CO_2. However, for this case, the sublimation process involved imposes a large energy penalty, which adds unnecessarily to the GWP impact. For the Vertical Injection and Dry Ice method, the final destination for CO_2 storage is at depths of 3000m. At this depth, the density of CO_2 is much greater than that of seawater and hence the tendency for it to escape is minimized (Caldeira at al., 2001).

Another viable option is Inclined Pipeline, where CO_2 is sequestered at depths of 2000m. For this option, CO_2 is transported via pipeline in compressed form; liquefaction of CO_2, which consumes huge amounts of energy, is not required (Sasaki, 2004). For both the Pipe Towed by Ship method and GLAD, the amount of potential

CO_2 leakage from the ocean to the atmosphere is rather large. The disposal depths for these two are 1500m, where the leakage rate is estimated to be 26% (Herzog et al., 2001). The GLAD system does not have the potential to store large amounts of CO_2, however, it offers an advantage of requiring very minimal energy usage (Niwa, 2004). Compared to the other four ocean sequestration options, the GLAD system itself hardly poses any environmental damage. This is due to the fact that the entire system does not require any liquefaction or transportation by ocean tankers for the final dissolution of CO_2 in the ocean.

5.3.2 Acidification

The Acidification results for both ocean and geological sequestration are displayed in Figure 5.10 below.

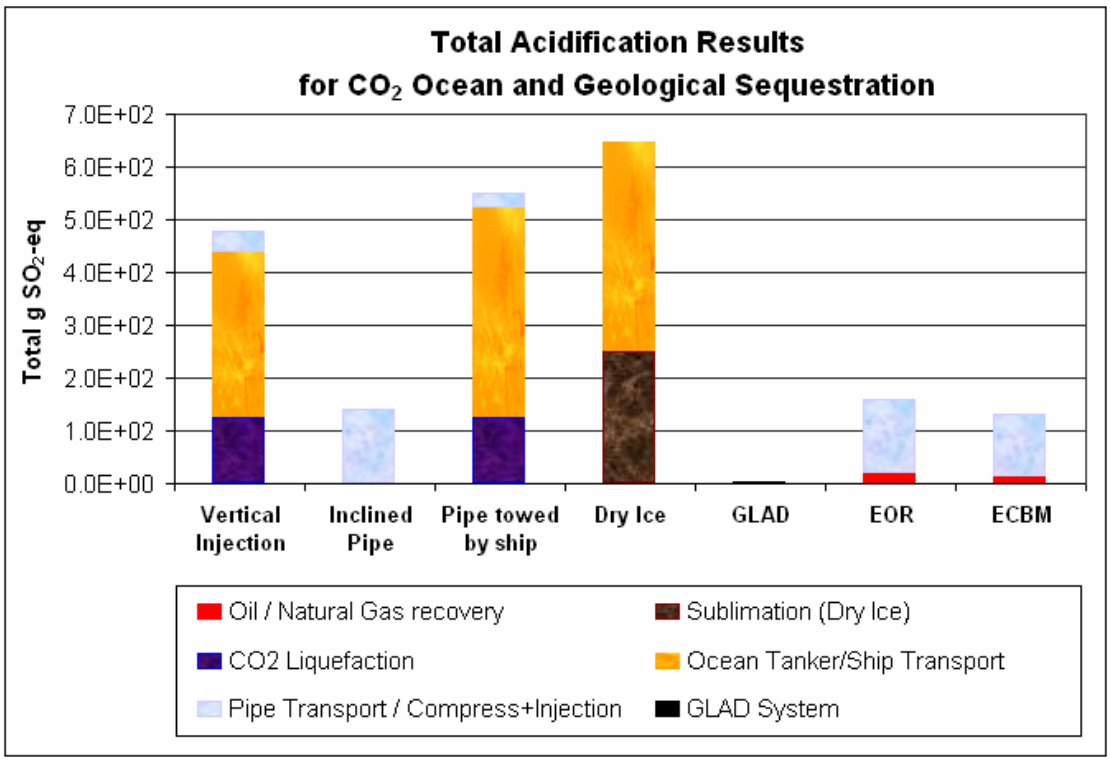

Figure 5.10. Acidification results for ocean and geological sequestration

Unlike the GWP graphs (Figure 5.9), the Acidification graphs (Figure 5.10) all display positive peaks. While the sequestration methods each offer a certain amount of potential to prevent GWP impacts, they contribute (add) to other areas of environmental damages. The large environmental impacts caused by ocean tanker transportation, mainly by the release of SOx and NOx, can be observed very clearly in the graphs. The acidic gases generated due to pipeline transportation are very small compared to those generated by the ocean tankers. The environmental impacts due to the liquefaction and sublimation processes are moderate in this impact category.

5.3.3 Human Toxicity to Air and Water

The environmental impacts of Human Toxicity to Air and Water are displayed in Figures 5.11 and 5.12 respectively. The graphs displayed by the Human Toxicity to Air and Water results exhibit the same trend. Significant environmental impacts are most evidently shown by the Dry Ice ocean sequestration option, due to the huge amount of energy required for the sublimation process required to produce solid CO_2. The process of CO_2 liquefaction for Vertical Injection and Pipe Towed by Ship also display rather significant peaks. For both cases, liquefaction of CO_2 is a necessary stage before it can be transferred in large amounts by ocean tankers. The environmental impacts due to pipeline transportation of CO_2 over long distances can also be realized from the graphs for both geological sequestration with EOR and ECBM, as well as from ocean sequestration of Inclined Pipeline.

For both geological sequestration systems, resources are recovered. Slightly higher energy is spent recovering oil (for EOR) than natural gas (for ECBM). But overall, the energy spent for resource recovery is relatively small.

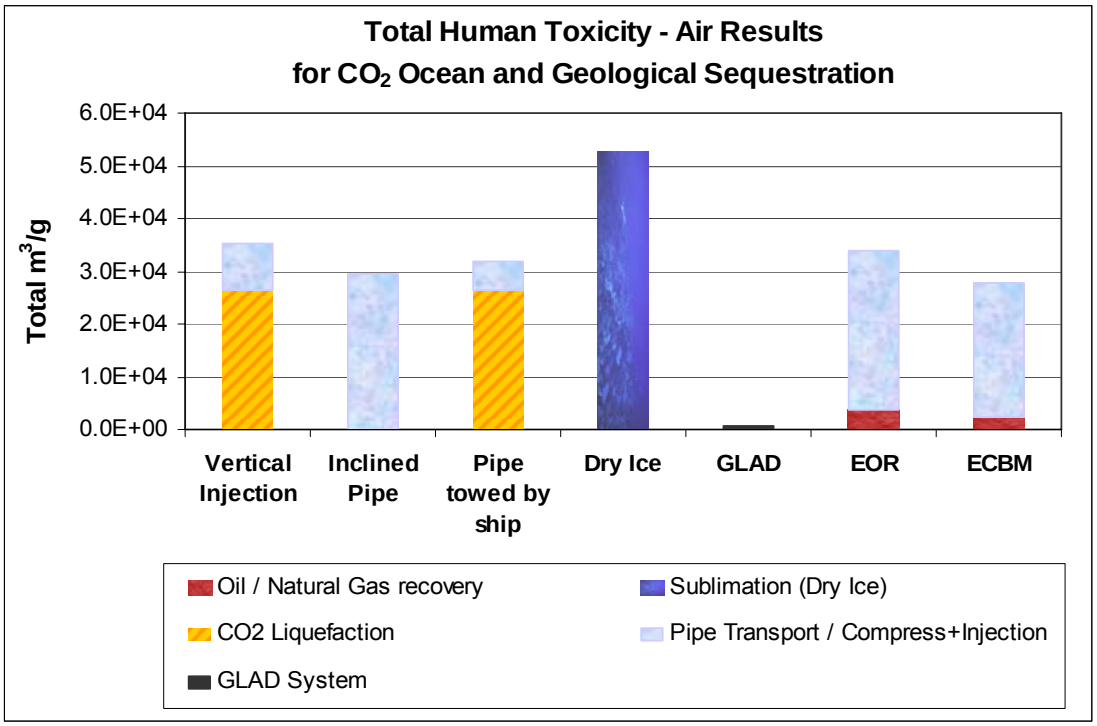

Figure 5.11. Human Toxicity to Air results for ocean and geological sequestration

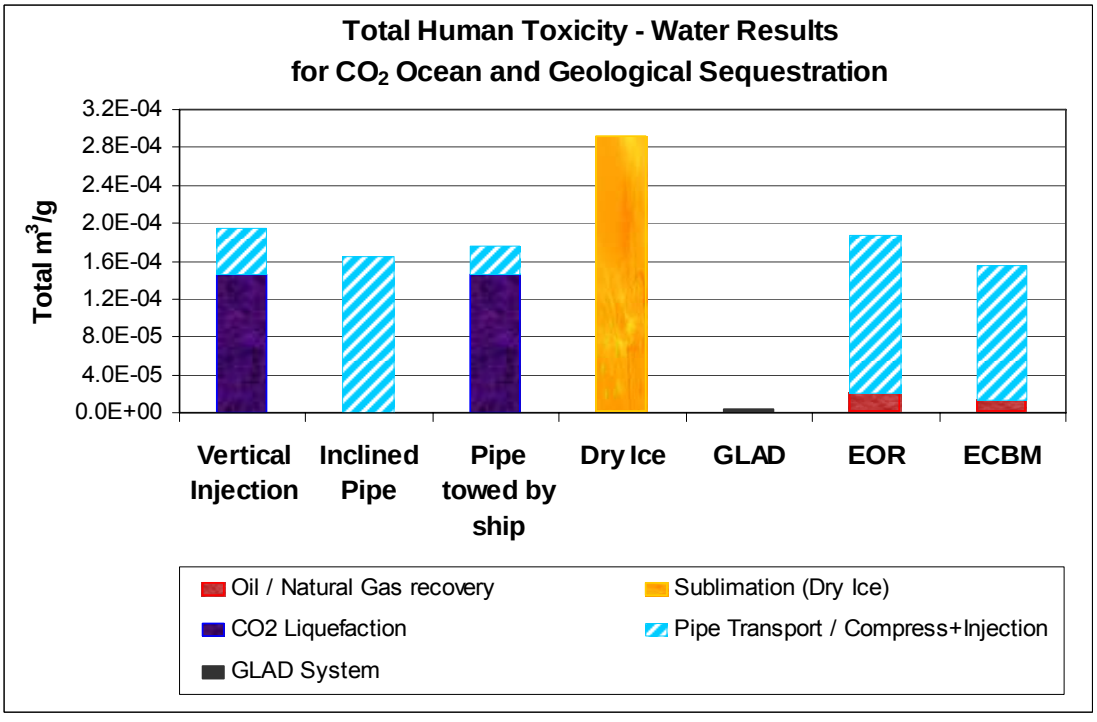

Figure 5.12. Human Toxicity to Water results for ocean and geological sequestration

5.3.4 Eutrophication and Ecotoxicity

The results of Eutrophication and Ecotoxicity are displayed in Figures 5.13 and 5.14 respectively. As expected, the CO_2 sublimation process from Dry Ice contributes most significantly to this environmental impact category. The CO_2 liquefaction process and pipeline transportation both generate relatively large amounts of wastewater from the power plant due to substantial energy demands – 120 kWh/ton CO_2 for liquefaction and about an average amount of 122 kWh/ton for long distance pipeline transportation of CO_2. These discharges contribute substantially to Eutrophication and Ecotoxicity. As for the GLAD, much less energy is required for dissolution, hence leading to nearly negligible environmental impacts.

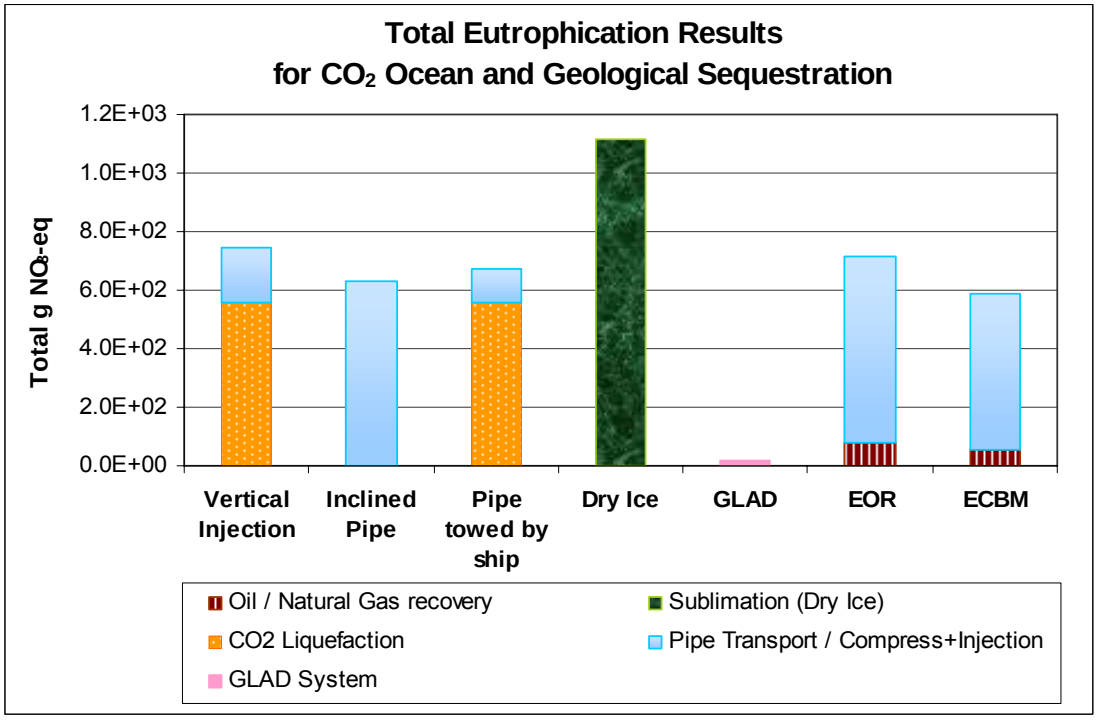

Figure 5.13. Eutrophication results for ocean and geological sequestration

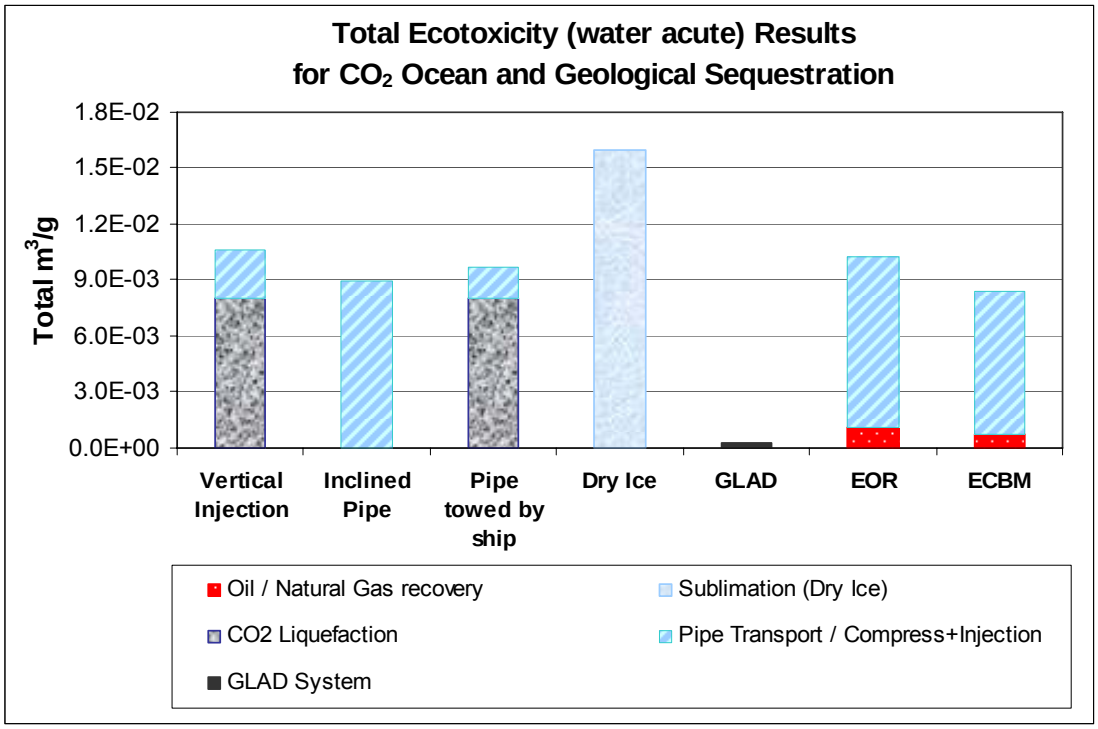

Figure 5.14. Ecotoxicity results for ocean and geological sequestration

5.3.5 Wastes and Resources

The results for Waste are displayed in Figure 5.15. In descending order, the sequestration systems that generates the highest to the least amount of wastes are: Dry Ice, Vertical Injection, EOR (geological), Pipe Towed by Ship, Inclined pipe, ECBM (geological) and finally, GLAD.

The Resource results for ocean and geological sequestration are displayed in Figure 5.16. The positive peaks exhibit the energy demands (resource consumed) for the sequestration systems – accumulated from CO_2 liquefaction process, transportation, compression, injection, etc.

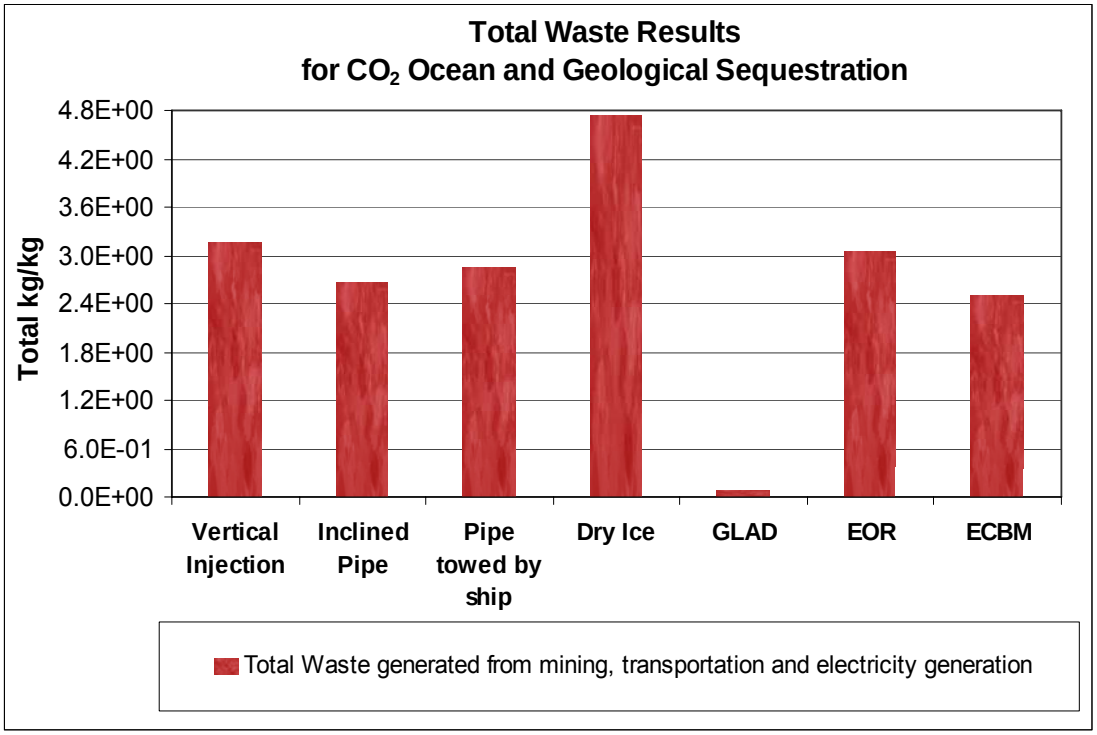

Figure 5.15. Waste results for ocean and geological sequestration

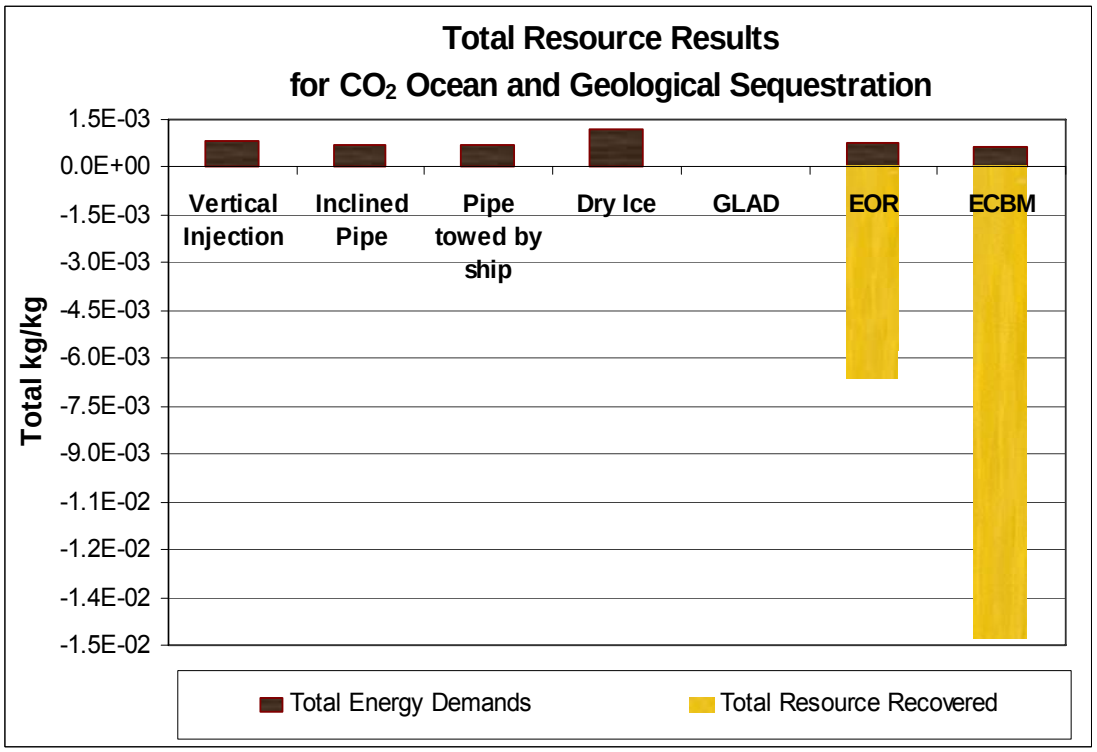

Figure 5.16. Resource results for ocean and geological sequestration

In Figure 5.16, the negative peaks demonstrate the potential amount of resources recovered (oil and natural gas) from the EOR and ECBM geological sequestration technologies. The inverted peaks are greater for ECBM due to the higher ratio of methane recovered, an estimated ratio of 1:3 (Reeves, 2003) as compared to the recovery of oil in EOR, which is approximated to be 0.18 ton for every ton of CO_2 injected (Aycaguer et al., 2001). Among the many solutions that contribute towards CO_2 mitigation, geological sequestration seems to be a promising path that presents the advantage of being able to cope with large volumes of anthropogenic CO_2 at stake, while fulfilling the growing energy demands of today's society.

5.4 Mineral Sequestration results

Finally for Mineral Sequestration, the results for Global Warming Potential, Acidification, Human Toxicity to Air, Human Toxicity to Water, Eutrophication, Ecotoxicity, Wastes and Resources for the ocean and geological sequestration systems are displayed in Figures 5.17, 5.18, 5.19, 5.20, 5.21, 5.22, 5.23 and 5.24 respectively.

5.4.1 Global Warming Potential

Figure 5.17 shows that among the five mineral carbonation processes, the most viable sequestration alternatives are methods 5 (using wollastonite) and next, 1 and 2 (both using olivine). Due to the high energy demands, predominantly from the Activation (Heat Treatment) processes, methods 3 and 4 contributes significantly to GWP. The energy requirements to activate the serpentine minerals are 2202 (for lizardite) and 829 (for antigorite) kWh/ton respectively for the complete sequestration of CO_2

(O'Connor et al., 2005). These two mineral sequestration methods end up adding more CO_2 into the atmosphere than can be sequestered.

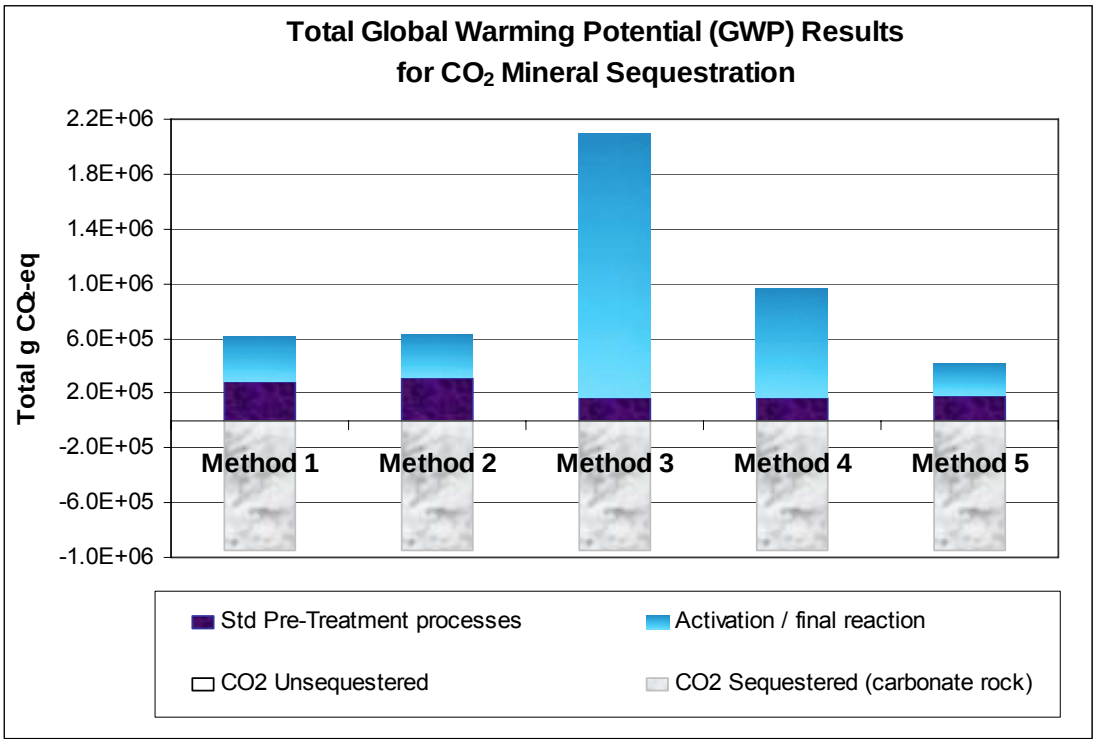

Figure 5.17. Global Warming Potential results for mineral sequestration

The graphs do not display any peaks for un-sequestered CO_2. This is because for each case, the energy requirements are calculated according to the 100% conversion of CO_2 into carbonate rocks (Dahlin, 2005).

5.4.2 Acidification

The results for Acidification are displayed in Figure 5.18. From here the significant impact on the environment due to Activation is very evident, especially for method 3. The Activation stages for all the minerals are necessary for the complete conversion of the CO_2 into a mineral rock (O'Connor et al., 2005). Although Mineral

Sequestration is suggested to be an environmentally friendly option based on the fact that the end product – mineral rock – is inherently safe (Goldberg et al., 2001), the method is threatened by the generation of huge environmental burdens due to its high energy demands.

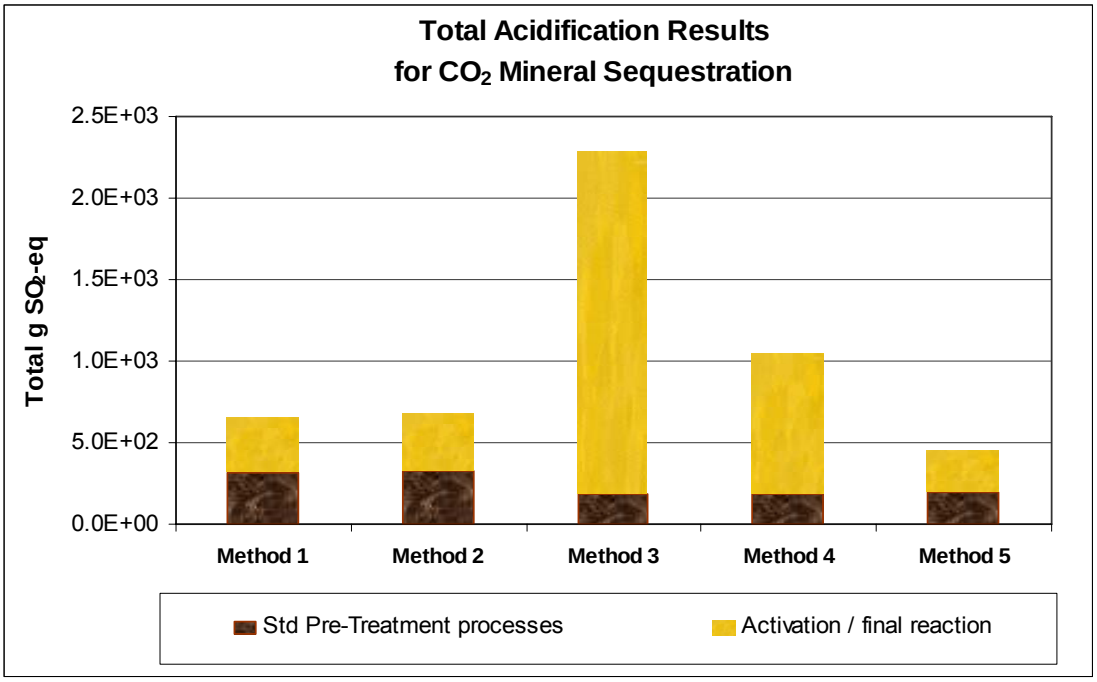

Figure 5.18. Acidification results for mineral sequestration

5.4.3 Human Toxicity, Eutrophication and Ecotoxicity

The results for Human Toxicity to Air, Human Toxicity to Water, Eutrophication and Ecotoxicity are displayed in Figures 5.19, 5.20, 5.21 and 5.22 respectively. It is expected that the four results (Figures 5.19 – 5.22) all display the exact same trend as those displayed by Figure 5.18 (Acidification). However, the order of magnitudes of the impacts (or peaks) is not the same for each of the four graphs. The release of pollutants from the chain of processes – mining, transportation and final generation of

electricity (supplied to the mineral sequestration plants) – all differ in types and quantities, and each will have different effects on the environment.

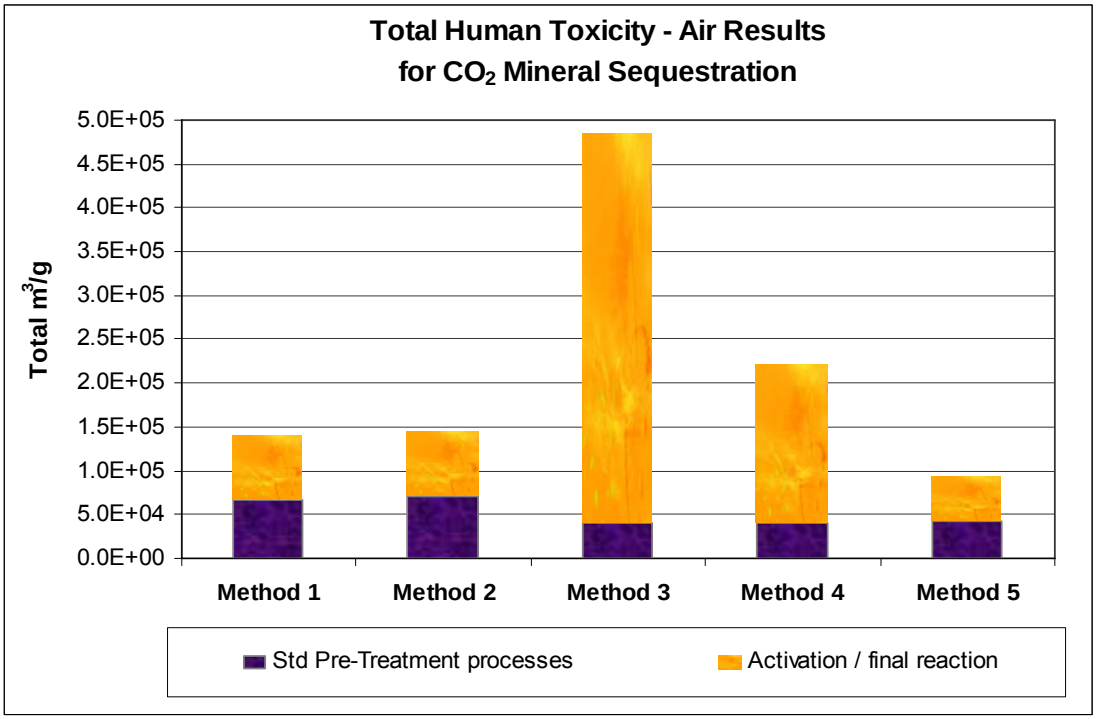

Figure 5.19. Human Toxicity to Air results for mineral sequestration

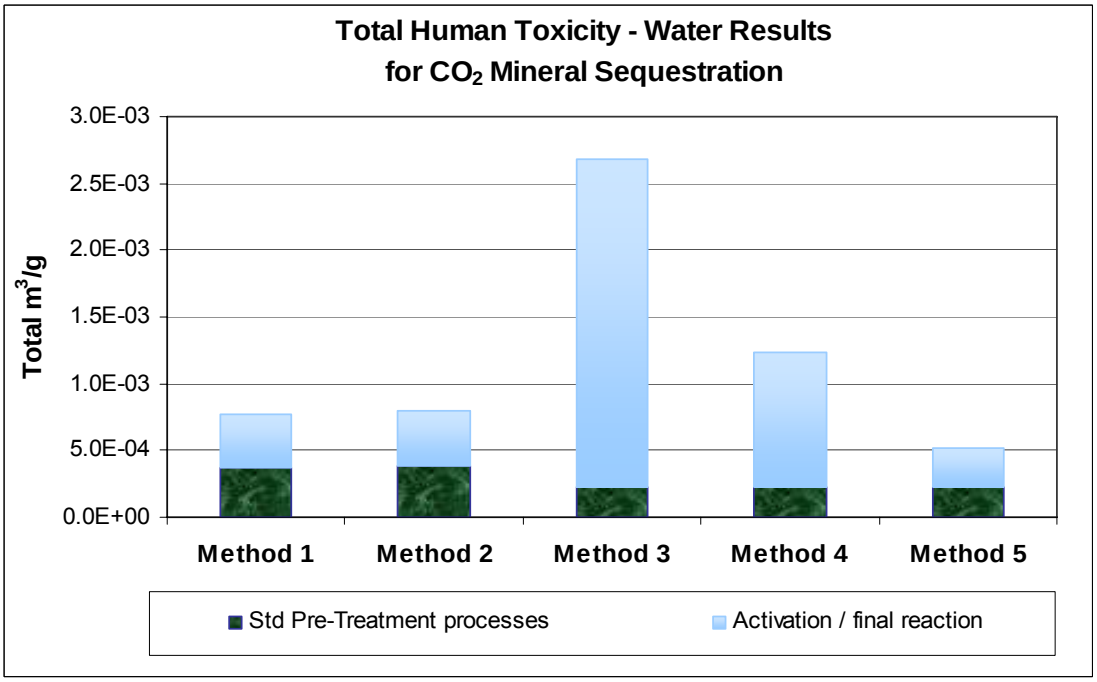

Figure 5.20. Human Toxicity to Water results for mineral sequestration

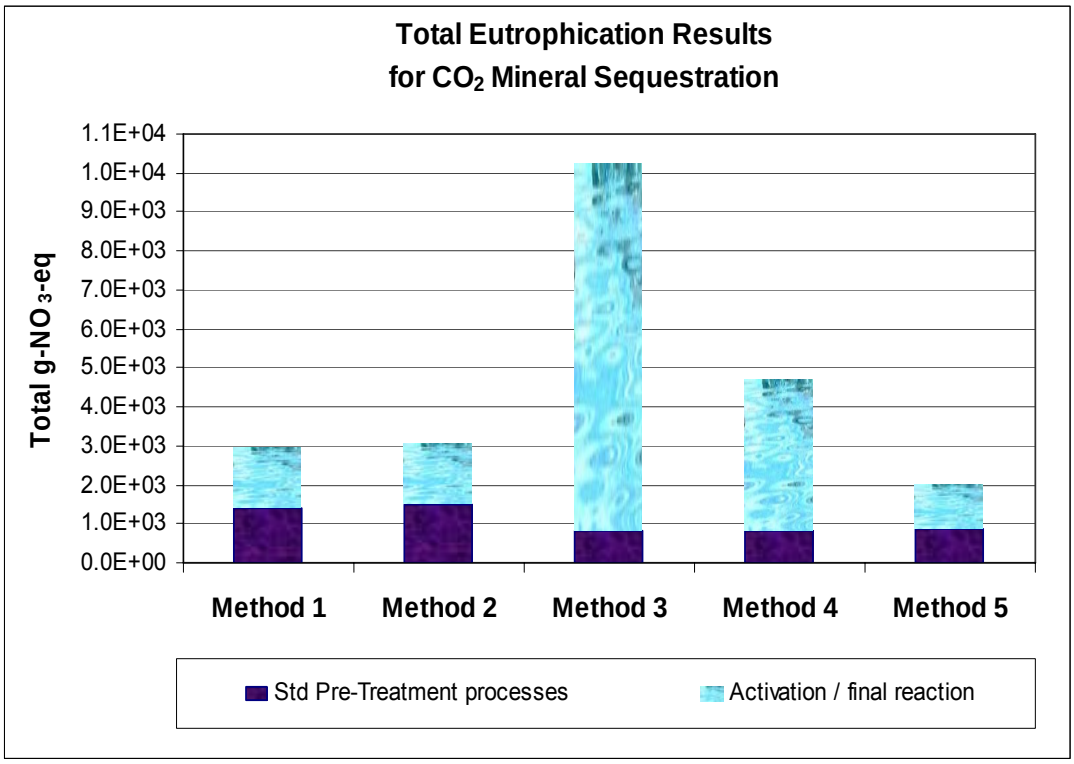

Figure 5.21. Eutrophication results for mineral sequestration

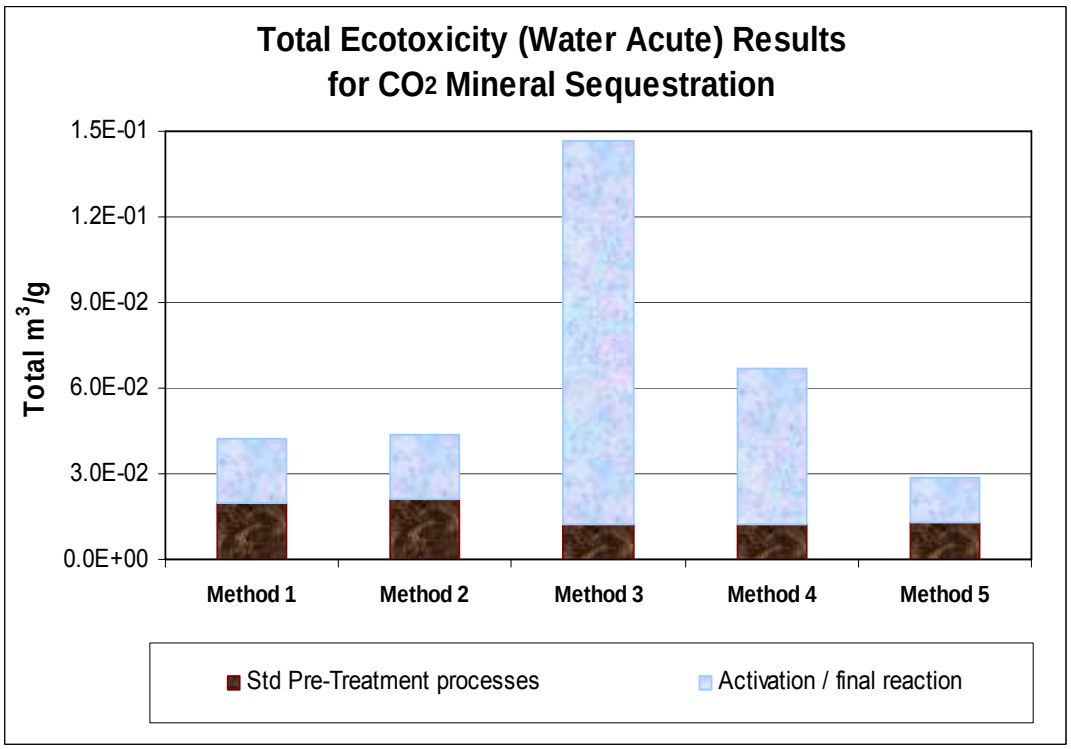

Figure 5.22. Ecotoxicity (water acute) results for mineral sequestration

Impacts leading to Human Toxicity to Air (Figure 5.19) and Water (Figure 5.20) are caused by the release of toxic substances, such as air emissions of heavy metals, water emissions containing metallic ions, etc., that are known to be potentially harmful to human health (Hertwich et al., 2001). Emissions of nitrogen oxides (NOx and NO_2) and ammonia (NH_3) are the principal contributors to the Eutrophication impact category (Figure 5.21). Finally, the Ecotoxicity (Figure 5.22) category is concerned with impacts on natural ecosystems, caused mainly by acids and sulfides.

CO_2 fixation via mineral carbonation has been considered as a safer option (Goldberg and Walters, 2002; Lackner, 2002), in comparison to ocean and geological sequestration. While "CO_2 leakage" from the other two sequestration storage sites can cause threats to both humans and the environment, in mineral sequestration this concern is absent. However, the results from Figures 5.19 to 5.22 highlight that although large-scale mineral sequestration plants have the potential to store of large amounts of CO_2, preliminary evaluations should be carried out to ensure that the processes involved in mineral carbonation do not themselves create excessive amounts of other environmental damage.

5.4.4 Wastes and Resources

The last two results, Waste and Resources, are displayed in Figures 5.23 and 5.24 respectively. One of the major concerns of electricity generation from fossil fuels is the volume of wastes coming from coal-fired power plants (Spath et al., 1999). In this LCA mineral sequestration system, the mining and transportation of mineral rocks have not been included in the LCA system. The waste from mining would have added considerably to the graphs shown in Figure 5.23. Also, the resources required

for mining would have also contributed to the final impact category (Figure 5.24) for all five mineral sequestration methods.

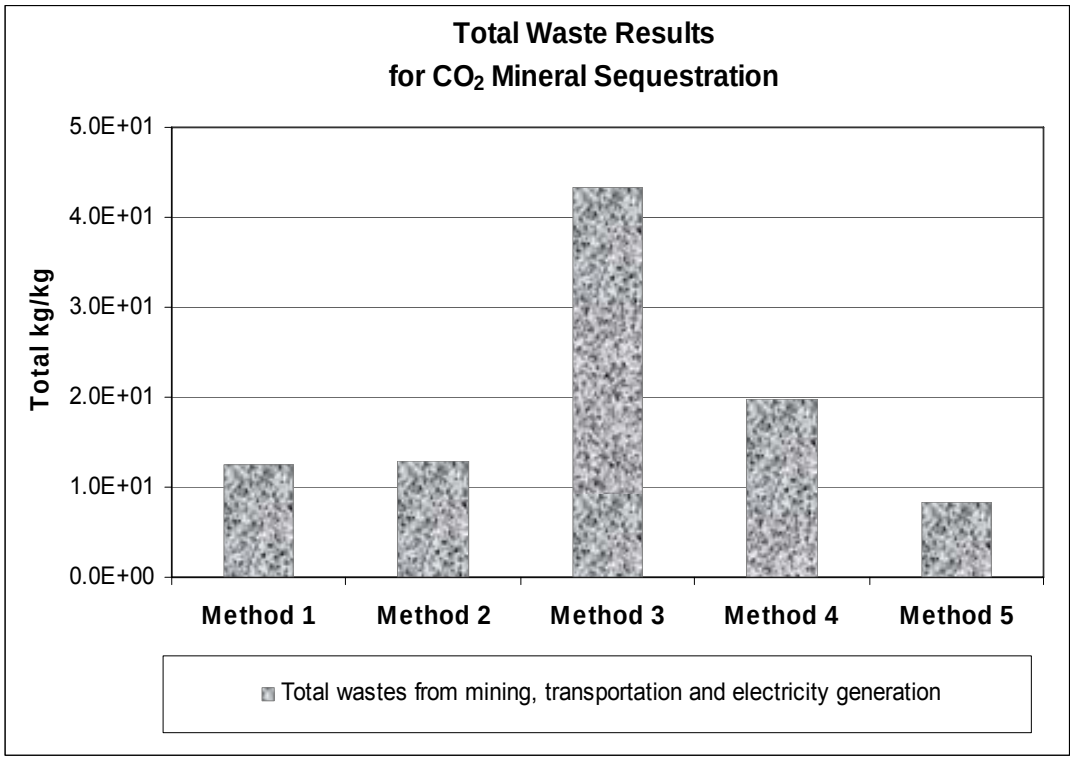

Figure 5.23. Wastes results for mineral sequestration

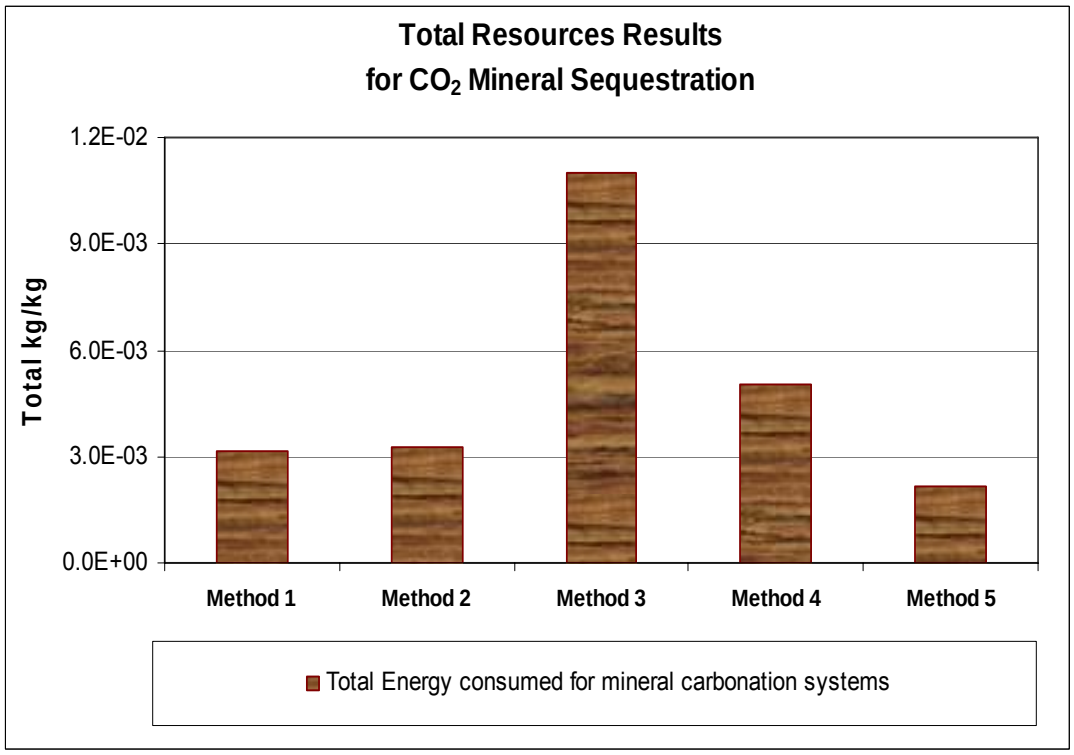

Figure 5.24. Resource results for mineral sequestration

As mentioned, mineral carbon sequestration is a longer-term option compared to other sequestration routes, but the processes involved so far has been rather energy intensive (O'Connor et al., 2005). Perhaps in future, elimination of the energy-intensive heat treatment steps could render the process more feasible.

5.5 Overall Comparison

Up to here, each of the eight impact results – GWP, Acidification, Human Toxicity to Air and Water, Eutrophication, Ecotoxicity, Wastes and Resources – presented for all four CO_2 recovery technologies and sequestration systems, does not determine or give an overall account of the **total impacts** created. This is provided in the next chapter, where the Final Scores, which is the collective effects of all eight environmental impacts, are calculated and presented.

CHAPTER 6

Further Discussions

CHAPTER 6

Further Discussions

6.1 Final (Weighted) Scores

In the previous chapter, the sets of results (total *characterized scores*) were generated using the EDIP 97 (SimaPro, 2005) impact assessment method based on the following set of assumptions:

- The Functional Unit of **1 MWh** from the power plant
- The emission levels of **950 kg-CO_2 per MWh** from the power plant
- For the four CO_2 recovery technologies, lower limits of CO_2 recovery rates of 95% (chemical absorption), 82% (membrane separation), 90% (cryogenics) and 85% (PSA) was used, along with the lower energy requirements of 330, 70, 600 and 160 kWh/ton respectively
- The CO_2 Recovery and Sequestration systems were treated as two separate (isolated) components.

The results for the potential environmental impacts (GWP, Acidification, Human Toxicity, etc) for the four CO_2 recovery technologies and a total of 12 sequestration systems were projected *individually* and *separately*. In this manner, no "overall verdict" can be reached because the results were displayed as an array of eight different impact categories.

In order to make overall comparisons, a **single final score** for each combination of options – as an undivided series of processes – must be attained. The calculations for

obtaining the final scores include two additional steps, known as Normalization and Weighting. Normalization transforms the magnitude of LCI and LCIA results into relative contribution by substance and life cycle impact category. The EDIP method uses the background contribution from the whole society as normalisation reference. There are several methods to assign Weighting values. SETAC workgroup on LCIA distinguished types of weighting as:

- monetary methods, such as society's willingness to pay (for environmental damage, illness, ecosystem disruptions)
- sustainability and target methods, such as in the distance-to-target procedure, and
- social and expert methods and/or panel approach.

An example of assigning weighting values in LCIA is described in Soares et al. (2006).

Weighting allows us to see the environmental trade-offs when comparing different activities within the same life cycle study, especially in the setting of priorities for pollution mitigation (Bengtsson and Steen, 2000). These calculations will be carried for a total of **48 combinations** (i.e., 4 CO_2 recovery x 12 sequestration options), based on the Main System Boundary that was displayed in Figure 4.0 (chapter 4).

Figure 6.1, which is a modified version of Figure 2.3 (chapter 2, pg. 26), illustrates the Normalization and Weighting steps to arrive at the **final scores.** In the on-going standardization effort of the International Organization for Standardization (ISO), weighting has been defined as an optional step and it is described as the process of converting indicator results by using numerical factors based on value choices, that is, based on the level of importance of various safeguard subjects (human health, air

quality, etc) selected (Hofstetter, 1999; Bengtsson and Steen, 2000). The purpose of weighting is to further illuminate decision situations and to clarify the final benefits or drawbacks of a system.

The Normalization values and Weights for the EDIP method are contained in **Appendix A.** The final results for all 48 combinations are displayed in Tables 6.1 (ocean and geological sequestration) and 6.2 (mineral sequestration).

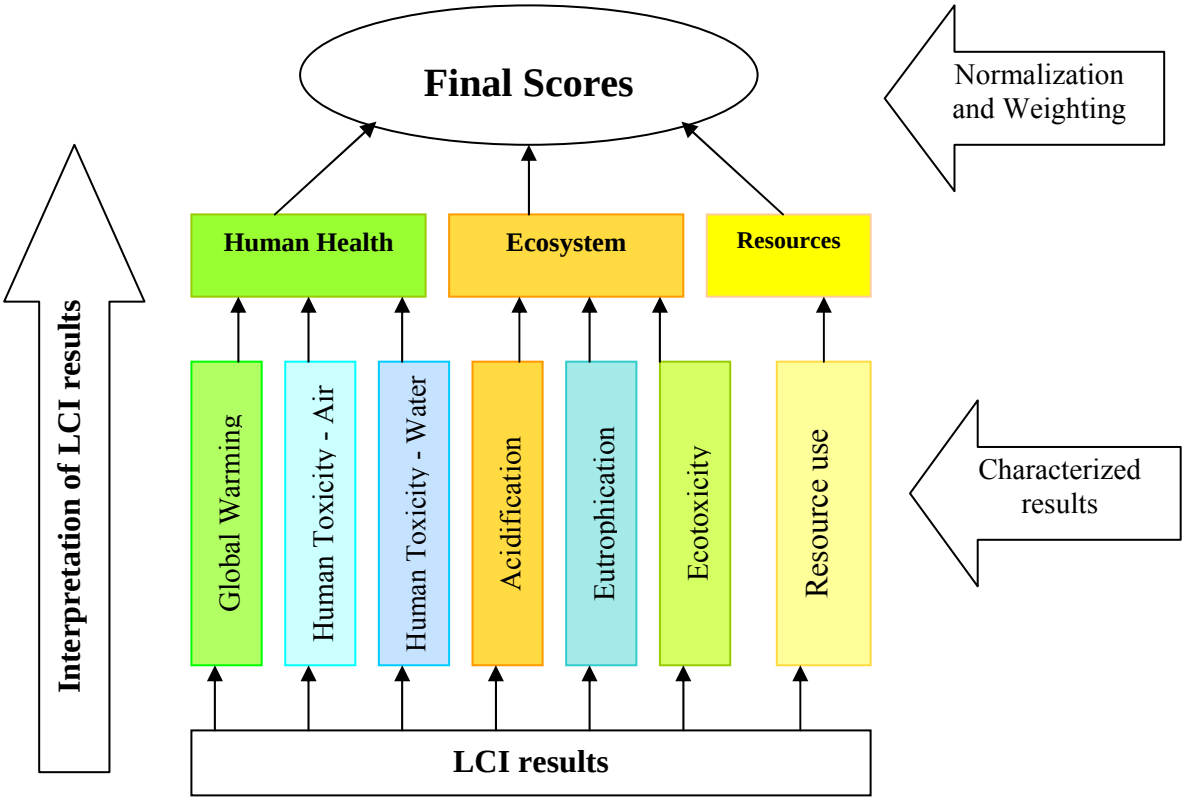

Figure 6.1. From LCI results to Final Scores

Table 6.1. Final scores of CO_2 Recovery Technologies combined with Ocean and Geological sequestration

CO_2 Recovery Technology and Recovery rate		OCEAN					GEOLOGICAL	
		Vertical Injection	Inclined Pipeline	Pipe towed by ship	Dry Ice	GLAD	With EOR	With ECBM
Chemical Absorption	**95%**	-6.2E-02	-4.6E-02	-9.0E-03	-4.6E-02	-3.6E-02	-7.8E-02	-1.0E-01
Membrane Separation	**82%**	-4.4E-02	-3.1E-02	9.7E-04	-3.0E-02	-2.4E-02	-5.8E-02	-7.9E-02
Cryogenics	**90%**	-3.5E-02	-1.5E-02	1.5E-02	-1.2E-02	-3.7E-03	-4.3E-02	-6.5E-02
Pressure Swing Adsorption	**85%**	-4.5E-02	-3.1E-02	1.9E-03	-3.0E-02	-2.4E-02	-6.0E-02	-8.1E-02

Note. All results are based on: Functional Unit = 1 MWh from the coal-fired power plant; generation of 950 kg-CO_2 per MWh; lower limits of CO_2 recovery

The final scores are totaled from the accumulation of all eight environmental damages (GWP, Acidification, Human Toxicity, Ecotoxicity, etc), starting with the generation of CO_2 due to **1 MWh** produced from the coal-fired power plant, to the CO_2 removed from the flue gas, next to the sequestration systems and finally to the storage of CO_2.

Table 6.1 shows that the "best" negative scores (least environmental burdens) stem predominantly from the two geological sequestration methods. The accumulated negative values for both EOR and ECBM methods are not only from the prevention of GWP, but also from the prevention of resource depletion. From the quantitative evaluation, the most promising environmental benefit is displayed by employing ECBM combined with chemical absorption. The next three highest benefits also come from geological sequestration – EOR with chemical absorption, and ECBM combined

with membrane separation and with PSA. The rest of the final scores for geological sequestration also suggest rather promising results.

As for ocean sequestration, the chief environmental advantage arises from combining chemical absorption removal technology with Vertical Injection. Reasonable (negative) scores are also demonstrated by all the other three CO_2 removal technologies with Vertical Injection. The second most feasible options are by Inclined Pipeline and Dry Ice disposal – both combined with the same chemical absorption recovery technology. The "worst cases" are displayed by combining any CO_2 removal methods with Pipe Towed by Ship. Most of the efforts taken for preventing potential global warming are suppressed by the generation of other environmental burdens, such as, toxic and acidic gases, wastewater and solid wastes. With the exception of using cryogenics to remove CO_2 from the power plant, all the final scores for the GLAD option display some small environmental benefits.

As displayed in Table 6.2, the most promising combination of mineral sequestration methods are presented by employing CO_2 removal using chemical absorption (95% recovery rate) with first of all, mineral sequestration method 5, followed by sequestration methods 1 and 2. The final scores for the rest of the same three mineral sequestration methods (utilizing wollastonite and olivine) combined with membrane separation, cryogenics and PSA all display reasonable environmental advantages.

Table 6.2. Final scores of CO_2 Recovery Technologies combined with Mineral Sequestration

CO_2 Recovery Technology and Recovery rate		MINERAL SEQUESTRATION				
		Method 1	Method 2	Method 3	Method 4	Method 5
Chemical Absorption	**95%**	-6.7E-02	-6.6E-02	3.0E-02	-4.4E-02	-8.0E-02
Membrane Separation	**82%**	-4.2E-02	-4.1E-02	6.4E-02	-1.7E-02	-5.6E-02
Cryogenics	**90%**	-2.9E-02	-2.8E-02	7.2E-02	-5.0E-03	-4.3E-02
Pressure Swing Adsorption	**85%**	-4.4E-02	-4.3E-02	6.1E-02	-1.9E-02	-5.8E-02

Note. All results are based on: Functional Unit = 1 MWh from the coal-fired power plant; generation of 950 kg-CO_2 per MWh; lower limits of CO_2 recovery

Method 4 may also be considered for CO_2 sequestration purposes due to the convenience of the large availability of serpentine (Park et al., 2003; Zevenhoven and Kohlman, 2001), except when combined with cryogenics technology, where huge amounts environmental impacts are created due to the energy consumed by both the sequestration and CO_2 removal system. Positive scores are observed for all combinations of CO_2 recovery technologies with method 3, which means that more environmental burdens are created than prevented. This highligts the importance of employing a holistic environmental assessment tool, such as LCA, to evaluate the potential environmental consequences of the sequestration system itself, before moving ahead to set up the actual plant.

6.1.1 Hypothesis testing (*t-test*)

In order to realize the significance of the conclusions made based on the Final Scores, hypothesis's t-tests are carried out for the following:

i. **Hypothesis 1**: Geological Sequestration (ECBM and EOR) method is the most promising solution for CO_2 mitigation.

ii. **Hypothesis 2**: Among all ocean sequestration options, the highest environmental benefits are displayed by combining chemical absorption with Vertical Injection, Inclined Pipeline and Dry Ice.

iii. **Hypothesis 3**: Among all the Mineral Sequestration processes, the "best" options are from combining chemical absorption with Methods 1, 2 and 5.

Calculations for t-test

For Hypothesis 1:

$\sum x_{1\,(Geological)}$ = - 0.564 and $N_1 = 8$; (from table 6.1)

$\sum x_{2\,(Ocean + Mineral)}$ = - 0.957 and $N_2 = 40$; (from tables 6.1 and 6.2)

By applying the formulas:

$$\sum d^2 = \sum x^2 - [(\sum x)^2 / N] \quad \ldots\ldots\ldots\ldots (i)$$

$$\sigma^2 = \sum d^2 / (N-1) \quad \ldots\ldots\ldots\ldots (ii)$$

$$\sigma_d^2 = (\sigma_1^2 / N_1) + (\sigma_2^2 / N_2) \quad \ldots\ldots\ldots\ldots (iii)$$

$$t = [\, x_1^{(mean)} - x_2^{(mean)} \,] / \sigma_d \quad \ldots\ldots\ldots\ldots (v)$$

The result of **t-test = 472.80.**

⇒ Therefore the claim that geological sequestration is the most propmising solution can be considered *extremely significant*.

For Hypothesis 2:

$\sum x_1$ (Vertical Injection, Pipeline, Dry Ice *w* chem. abs) = - 0.154 and $N_1 = 3$; (table 6.1)

$\sum x_2$ (Other Ocean options) = - 0.352 and $N_2 = 17$; (table 6.1)

By applying formulas (i) to (iv), the resulting **t-test = 30.08**.

⇒ The claim that, among all ocean sequestration options, chemical absorption combined with Vertical Injection, Inclined Pipeline and Dry Ice offer the highest environmental benefits can be considered *very significant*.

For Hypothesis 3:

$\sum x_1$ (Mineral Methods 1, 2 & 5 w chem. abs) = - 0.212 and $N_1 = 3$; (from table 6.2)

$\sum x_2$ (Other Mineral methods) = - 0.241 and $N_2 = 17$; (from table 6.2)

By applying formulas (i) to (iv), the resulting **t-test = 2.42**.

⇒ This shows that the conclusion for Methods 1, 2 and 5, combined with chemical absorption, as being the "best" options for mineral sequestration is *rather insignificant*.

The detailed calculations for all three t-tests are compiled in **Appendix C**.

6.1.2 Error Analysis (Percentage Error)

Error Analysis is performed to estimate the errors in the final results, given the errors (fluctuations) in the starting numbers entered for the system, in this case, the LCA model. The actual values of errors for any of the measurements performed for CO_2 sequestration are unavailable.

Since no experimental set-up exists in Singapore for generating the parameters (LCI data) for the project, an estimated error of 10% is assumed throughout the LCI data.

By employing the *Additive Formulae* for Error Analysis (Taylor, 1997), it is projected that when the LCI data are all given an error of 10%, the associated new LCIA results will also change very closely by the same percentage. A step-by-step calculation to prove this is illustrated in **APPENDIX D.**

Another approach, known as Uncertainty Analysis or **Sensitivity Analysis** (Steen, 1997), is carried out for the LCA. The purpose of Sensitivity Analysis is to test the difference in LCIA results generated when the 'input parameters' of the system are varied according to higher or lower (+/-) values, i.e., different CO_2 recovery efficiencies or higher CO_2 emissions from the power plant.

6.2 Sensitivity Analysis (Uncertainty Analysis)

In an LCA, sensitivity analysis is carried out for estimating the effects on the outcome of a study based on certain chosen methods, estimations and data. In this section, Sensitivity Analysis is carried out for comparing:

i Lower and upper limits of CO_2 Recovery Technologies

ii Power plant CO_2 emissions of: 950, 970 and 990 kg per MWh

iii Different levels of EDIP weights – low, med (unchanged), high

iv EDIP vs. Eco-indicator

6.2.1 Lower and Upper Limits of CO_2 Recovery Technologies

Based on Table 4.5 (chapter 4, pg. 62), the *upper limits* of the CO_2 recovery rates and energy requirements are taken as: 98% and 340 kWh/ton (chemical absorption); 88% and 75 kWh/ton (membrane separation); 95% and 660 kWh/ton (cryogenics); 90% and 180 kWh/ton (for PSA).

The results for comparing the *lower and upper limits* of CO_2 Recovery with geological and ocean sequestration are shown below in Figures 6.2. The results for comparing the *lower and upper limits* of CO_2 Recovery with mineral sequestration are shown below in Figures 6.3.

For Vertical Injection, the improvements for the Final Scores are 12%, 26%, 27% and 22% respectively when the CO_2 recovery efficiencies are raised from 95% to 98% for chemical absorption, 82% to 88% for membrane separation, 90% to 95% for cryogenics and from 85% to 90% for PSA. Improvements of about 15-30% can be realized for the Inclined Pipeline ocean sequestration method with chemical absorption, membrane separation and PSA, and up to 45% with Cryogenics. For the Pipe Towed by Ship method, an improvement of up to 40% of the final scores is achieved with chemical absorption and over 50% with the rest. However, it can be seen from Figure 6.2 that some of the scores for this ocean sequestration option still remain as positive peaks, which further confirms that it is not a feasible option.

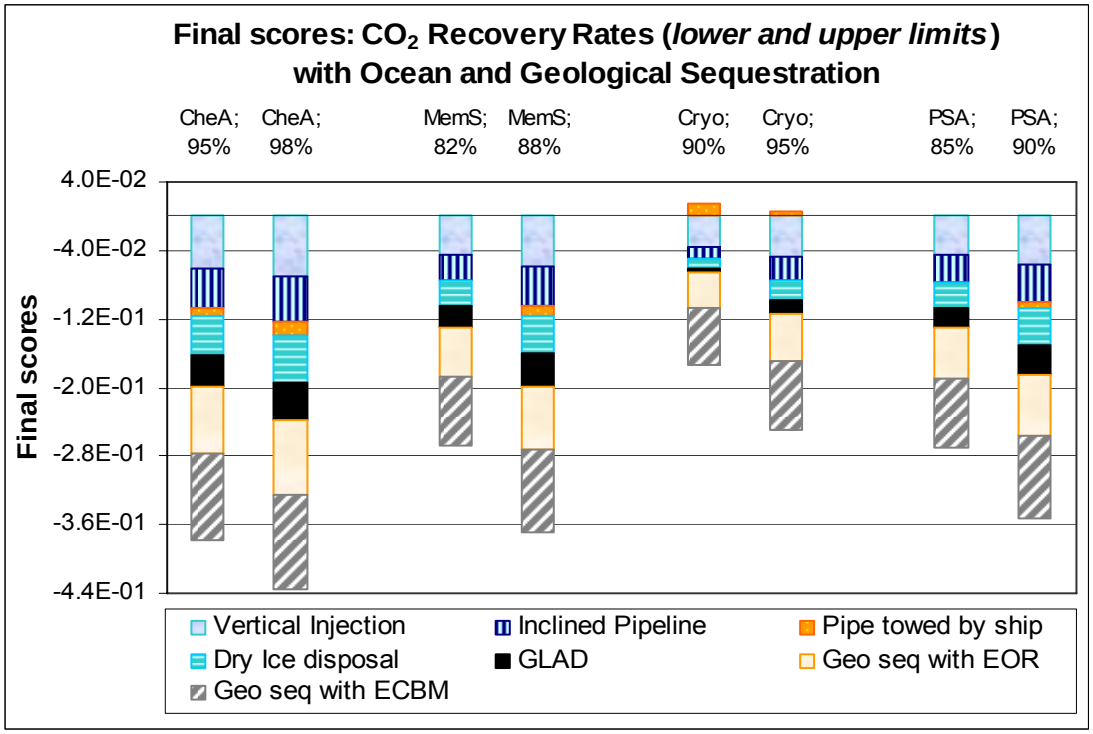

Figure 6.2. CO_2 recovery with ocean and geological sequestration

Note: CheA = Chemical Absorption; MemS = Membrane Separation; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

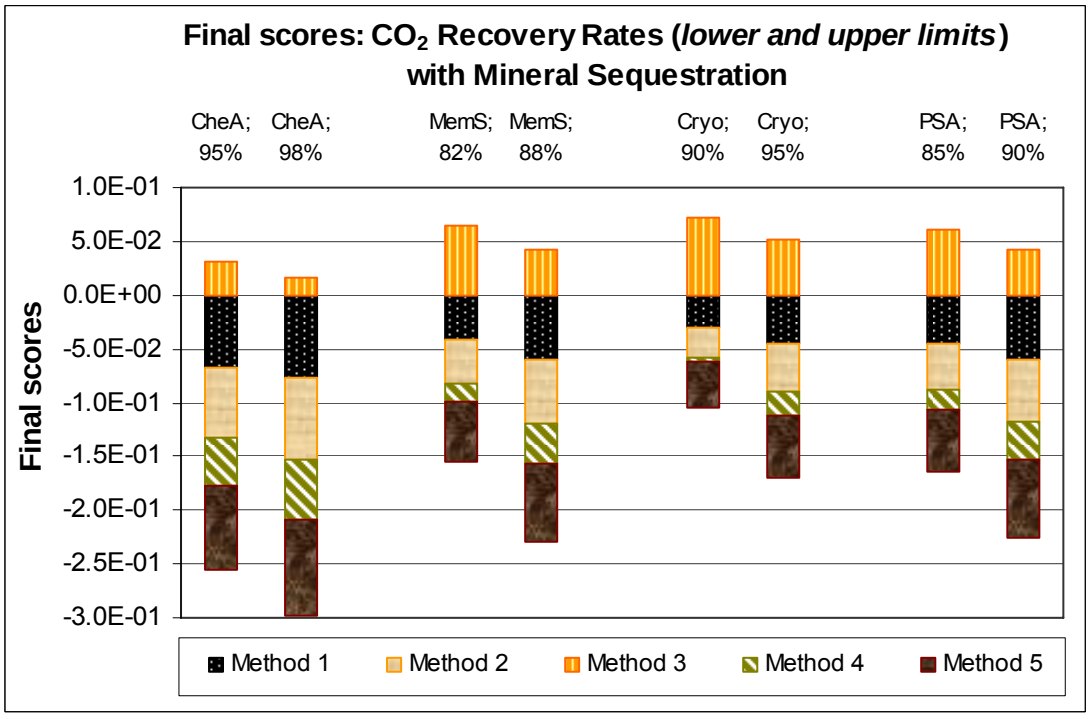

Figure 6.3. CO_2 recovery with mineral sequestration

Note: CheA = Chemical Absorption; MemS = Membrane Separation; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

As for Dry Ice and GLAD, both ocean sequestration systems show gradual improvement of 15% and 16% with chemical absorption, 33% and 35% with membrane separation, 51% and 74% with cryogenics, and finally 28% and 30% with PSA. Also from Figure 6.2, the final scores for the two geological sequestration methods have both improved substantially, from 9% (ECBM) and 10% (EOR) with the *upper limits* of the CO_2 recovery by chemical absorption, and 18-22% for membrane separation, 19-24% for cryogenics and finally 15-18% for PSA.

As seen from Figure 6.3, methods 1 and 2 both improve by approximately 14% each with a 98% recovery rate of CO_2 (by chemical absorption), 31% and 32% respectively with 88% recovery of CO_2 (by membrane separation), 36% and 37% respectively with 95% recovery of CO_2 (cryogenics), and 26% each with PSA (with 90% recovery of CO_2). For mineral sequestration with method 3, which utilizes serpentine-lizardite, large differences from 40% to 44% are realized with cryogenics and PSA, and over 50% with the others.

Although the environmental burdens for method 4 have all reduced – from 20% to over 50% – they still remain as positive peaks. This confirms that method 4, which utilizes serpentine-antigorite, is verified to be the least feasible mineral sequestration option. Finally for method 5 (wollastonite), the improvements are from 11% for chemical absorption and from 20-25% with the other three CO_2 recovery technologies.

6.2.2 Power Plant Emissions of 950, 970 and 990 kg CO_2

The final scores for combining the CO_2 removal technologies (all *lower limits*) combined with the sequestration techniques – based on a power plant with CO_2 emission values of 950kg, 970kg and 990kg for every MWh of electricity generated – are shown in Figures 6.4 (ocean and geological) and 6.5 (mineral).

Figure 6.4 shows that for the four CO_2 removal technologies combined with ocean and geological sequestration, small increments of 2% or 4% increase in scores are realized as the amount of CO_2 emissions increased from 950kg/MWh to 970kg/MWh, or from 950 to 990 kg/MWh.

Figure 6.5 shows approximately the same percentage of improvements, that is, an average of 2% (from 950 to 970 kg-CO_2/MWh) and 4% (from 950 to 990 kg-CO_2/MWh). The explanation for the repeated trend is as follows. As the power plant's CO_2 emissions increase by a certain amount, nearly the same proportion of the gas gets recovered and sequestered.

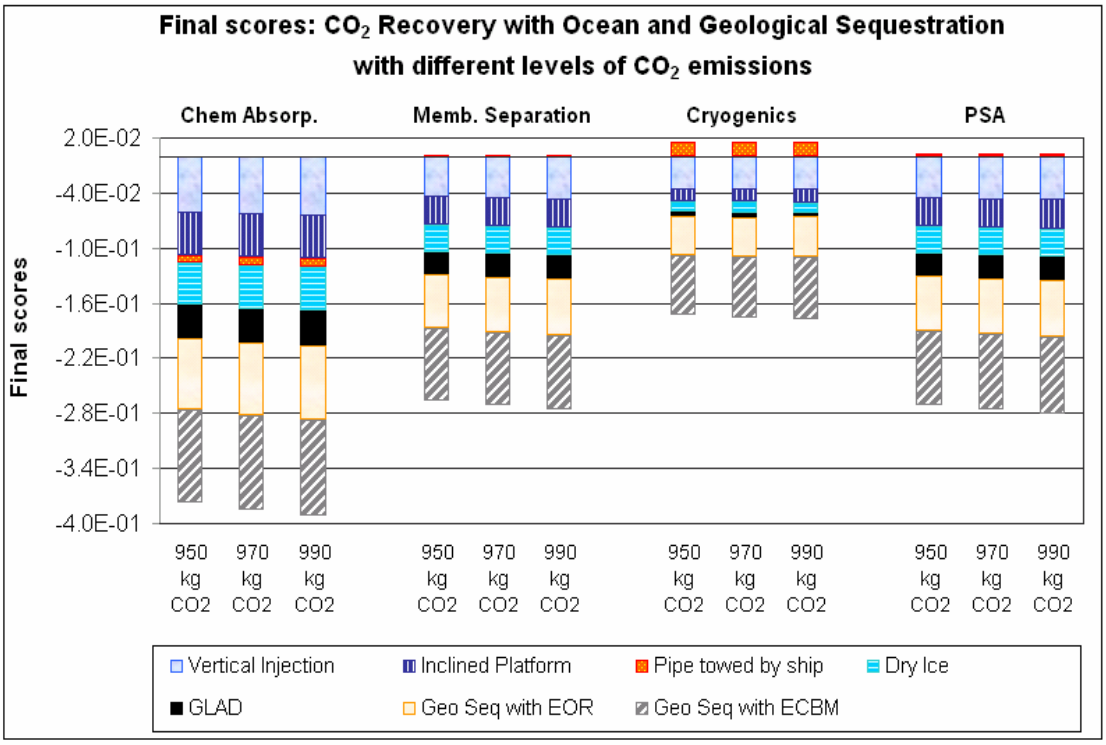

Figure 6.4. CO_2 recovery combined with ocean and geological sequestration with power plant emissions of 950, 970 & 990 kg-CO_2 per MWh

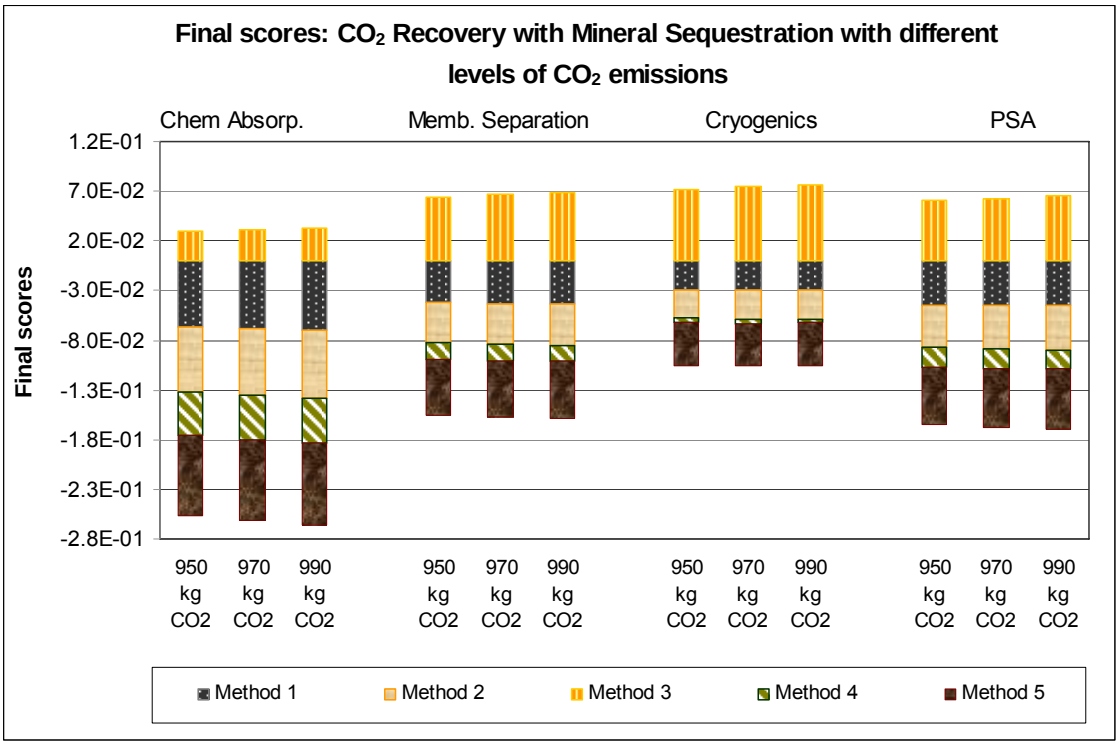

Figure 6.5. CO_2 recovery combined with mineral sequestration with power plant emissions of 950, 970 & 990 kg-CO_2 per MWh

6.2.3 Comparison of Med, Low and High Weights

The first set of final scores, displayed in Tables 6.1 and 6.2, were derived according to the EDIP methodology. The sets of Normalization values and Weights (displayed in **Appendix A**) for GWP, Acidification, Human Toxicty to Air and Water, Eutrophication, etc. are taken as the "Med" (Medium) or un-changed EDIP values.

The same impact assessment calculations are now performed for "Low" and "High" Weights for all the environmental impact categories. The "Low" Weights are taken as **1.1**, which was allocated to Wastes and Resources in the "Med" EDIP; and the "High" Weights, taken as **2.8**, which was allocated to Human Toxicity to Air. The normalized and characterized scores of the EDIP method will remain un-changed. A summary of the, "Med", "Low" and "High" Weights are compiled in Table 6.3.

Table 6.3. "Med" (unchanged EDIP), "Low" and "High" Weights

Environmental impact category	Weights		
	"Med" (unchanged EDIP)	"Low"	"High"
Global Warming Potential	**1.3**	**1.1**	**2.8**
Acidification	**1.3**	**1.1**	**2.8**
Human Toxicity - Air	**2.8**	**1.1**	**2.8**
Human Toxicity - Water	**2.5**	**1.1**	**2.8**
Eutrophication	**1.2**	**1.1**	**2.8**
Ecotoxicity (Water Chronic)	**2.6**	**1.1**	**2.8**
Wastes	**1.1**	**1.1**	**2.8**
Resources	**1.1**	**1.1**	**2.8**

The final scores for comparing the "Med", "Low" and "high" Weights are shown in Figure 6.6 (ocean and geological sequestration) and 6.7 (mineral sequestration).

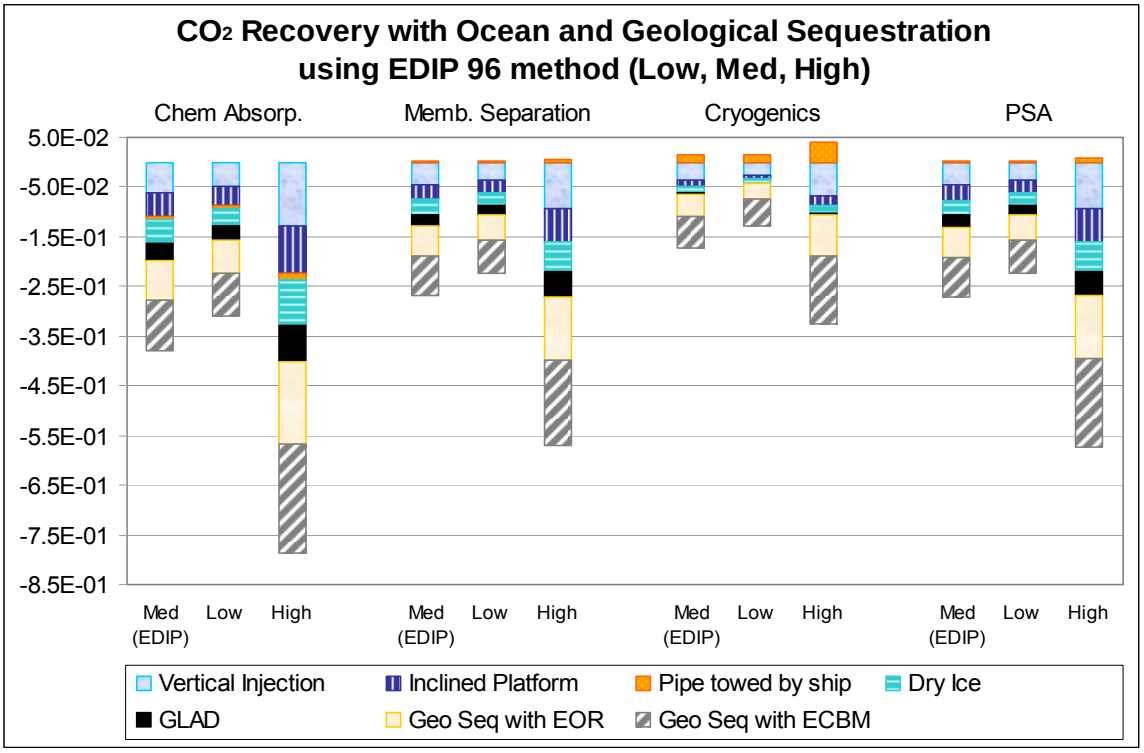

Figure 6.6. CO_2 recovery combined with ocean and geological sequestration using EDIP (Med, Low and High Weights)

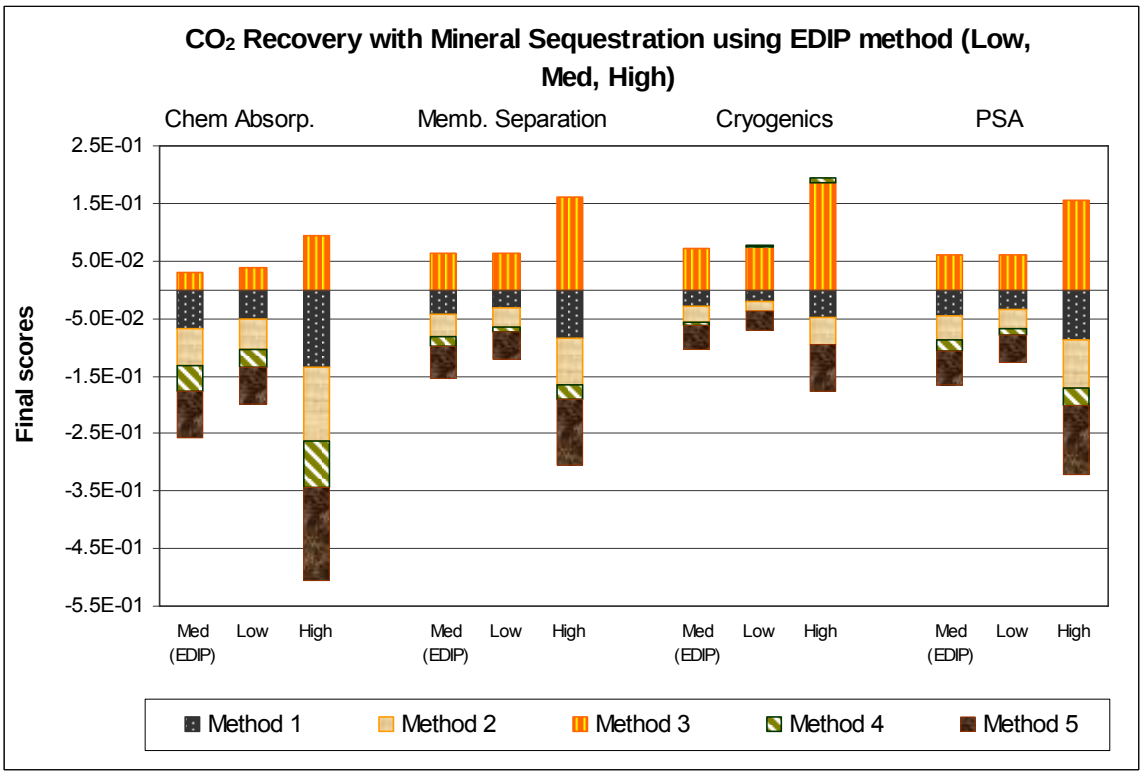

Figure 6.7. Final scores for CO_2 recovery combined with mineral sequestration using EDIP (Med, Low and High Weights)

As observed in Figure 6.6, four of the ocean sequestration options – Vertical Injection, Inclined pipe, Dry Ice and GLAD – in combination with chemical absorption, membrane separation and PSA, all exhibit reductions in environmental impacts of 21% to 26% with the 'Low" weights; and increases of 50% to 53% with the "High" weights. Vertical Injection combined with Cryogenics display 31% and 49% changes with "Low" and "High" weights respectively. As for the Inclined Pipeline, Dry Ice and GLAD combined with the same CO_2 recovery system, large fluctuations of about 80% and 20% are observed for the "Low" and "High" weights respectively.

The Pipe Towed by Ship method display fluctuations of over 50% (reduction) and 35% (increase) with chemical absorption for "Low" and "High" weights respectively; and 35%-43% (reductions) and over 60% (increases) with the other three CO_2 recovery technologies for "Low" and "High" weights respectively.

Also displayed in Figure 6.6, for geological sequestration (EOR and ECBM) combined with all four CO_2 recovery technologies, the differences in the total environmental impacts are approximately 16% to 26% from the "Med" to the "Low" weights, and approximately 50-55% from the "Med" to the "High" weights.

As seen from Figure 6.7, mineral sequestration methods 1, 2 and 5, in combination with chemical absorption, membrane separation and PSA, all exhibit reductions in final scores between 23% to 29% with the 'Low" weights; and increments of 50%-52% with the "High" weights. The final scores for same three sequestration methods are observed to reduce by 51-54% (methods 1 and 2) and 35% (method 5) from the

"Med" to the "Low" weights; and increase by 40-47% (methods 1, 2 and 5) from the "Med" to the "High" weights.

The reductions in the final scores for Method 3 for the "Low" weights are very small – an average 4% for all four CO_2 recovery systems. However, from the "Med" to the "High" weights, method 3 displays an increase of 62% on average, also when combined with all four CO_2 recovery technologies. Reductions of 34-44% are observed for method 4 with PSA, membrane separation and chemical absorption with the "Low" weights; and from 41% to 67% increments with the same three CO_2 recovery systems for the "High" weights. Sequestration method 4 combined with Cryogenics fluctuates significantly with the "Low" and "High" weights – for about more than 100% each.

6.2.3.1 Increased Weights for Human Toxicity

While holding all the rest of the weights constant (Table 6.3 "unchanged"), the Weightage for Human Toxicity to Air and Water were both increased, first to **2.8** and then to **3.0**. The results for the Final Scores were generated again. The results are shown in Table 6.4.

Table 6.4. Human Toxicity Weightage and Final Score Results

Weight for Human Toxicity (Air and Water)	**2.8**	**3.0**
Final Weighted Scores	No noticeable changes	No noticeable changes

The explanation for this is as follows. In the EDIP methodology, the consideration for Human Toxicity has already been given high consideration. The "heavy weights" for the Human Toxicity impact category are well suited for densely populated places found in some regions in Europe and Asia.

6.2.3.2 Increased Weights for Global Warming Potential

The same procedure is performed for the GWP impact category, where high weightages are expected to be imposed in places like North America in the near future. The results are displayed in Figures 6.8 and 6.9 below.

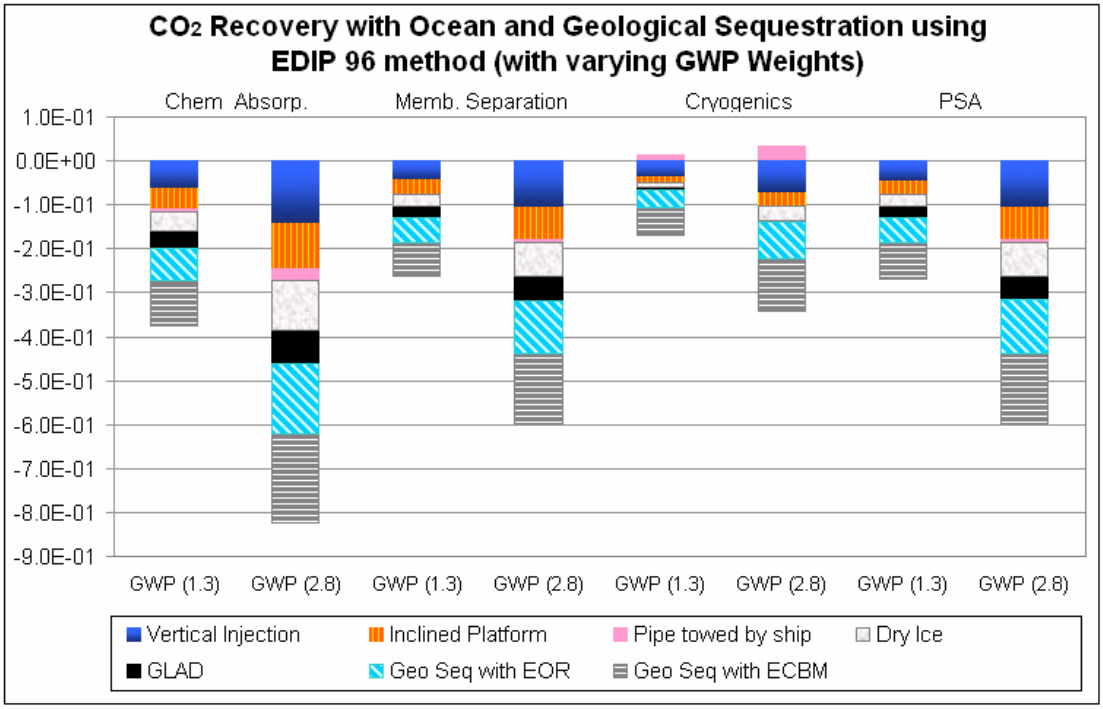

Figure 6.8. Final Weighted Scores for Ocean and Geological Sequestration based on varying GWP Weights

For Vertical Injection and Inclined Pipeline, the final scores all improved by about 50 – 58%. The Dry Ice option showed improvements of 59 – 66%. Tremendous jumps

were observed for Pipe Towed by Ship and GLAD, the final scores for these two ocean sequestration options improved from about 55% to over 100%. As for EOR and ECBM, moderate improvements were observed for both, that is about 46 – 50%.

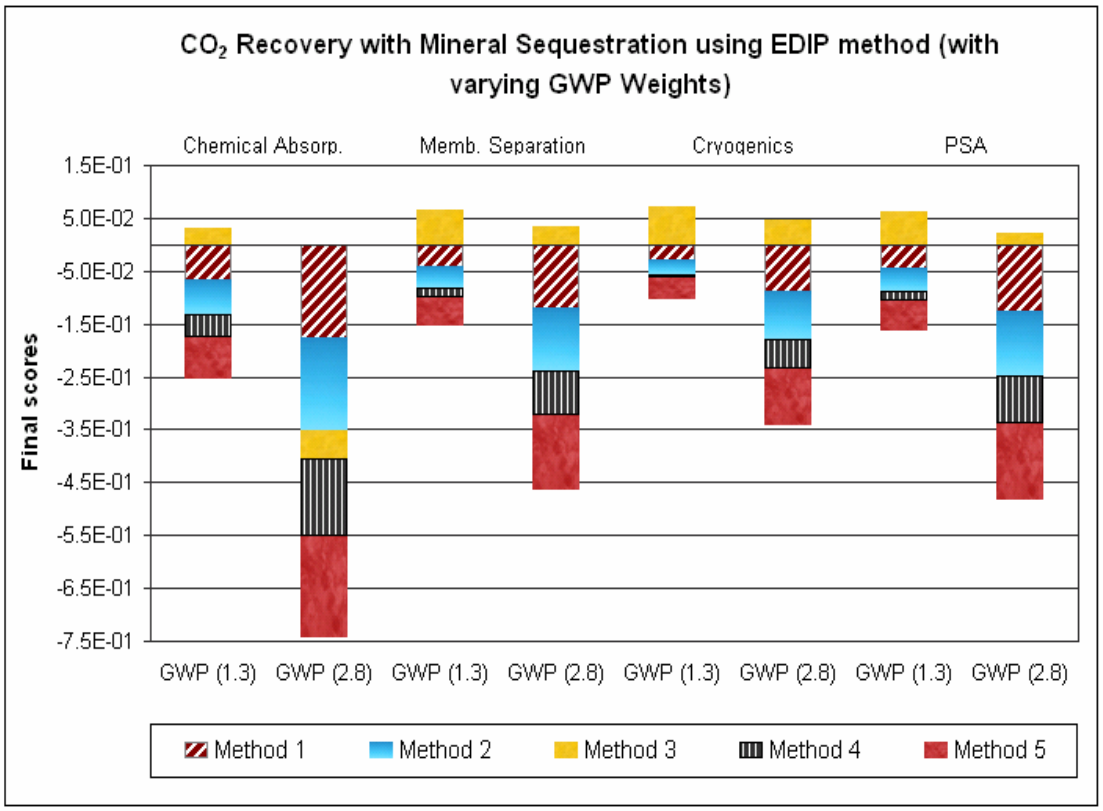

Figure 6.9. Final Weighted Scores for Mineral Sequestration based on varying GWP Weights

From Figure 6.9, it can be observed that the final scores for Methods 1 and 2 both improve by approximately 61-68%. Method 4 improved by 70-90% and Method 5 showed moderate improvements of 58-60%. As for Method 3, drastic changes were observed for the final scores – an improvement of 58% was realized when combined with Cryogenics, and over 100% with the rest.

6.2.4 EDIP vs. Eco-indicator

Up to here, the EDIP impact assessment methodology has been applied. Another impact assessment method, the Eco-indicator '99, will now be employed to generate the final scores for the combined processes of CO_2 recovery and sequestration. Unlike the EDIP, which adopts a *problem-oriented approach*, the Eco-indicator is a *damage-oriented approach*. The Eco-indicator provides three damage categories (SimaPro, 2005): ***Human Health***, ***Ecosystem Quality*** and ***Resources.***

Human Health. This is measured in DALY (Disability adjusted life years); that is, the different disabilities caused by diseases are weighted. Climate Change, Respiratory Organics, Respiratory Inorganics and Carcinogen are categorized under this damage category.

Ecosystem Quality. This is measured in PDF*m2yr, which is the Potentially Disappeared Fraction of plant species. The impact category of Acidification is listed under this environmental category. In terms of Ecotoxicity, the measured aspect is the percentage of all species present in the environment living under toxic stress (Potentially Affected Fraction or PAF*m2yr).

Resources. The last category measures the additional energy requirement to compensate lower future ore grade, and the unit of measurement is in MJ Surplus.

The Normalization and Weighting parameters used by SimaPro's Eco-indicator '99 (*Hierarchist-Average* version) for environmental impact calculations are shown in Table 6.5.

Table 6.5. Parameters of Eco-indicator 99

Environmental Impact Category	Damage Category	Hierarchist-Average (H/A) version	
		Normalized Values	Weights
Climate Change (DALY) Respiratory Organics (DALY) Respiratory Inorganics (DALY) Carcinogen (DALY)	Human Health	65.1	400
Acidification (PDF*m2yr) Ecotoxicity (PAF*m2yr)	Ecosystem Quality	1.95E-04	400
Fossil Fuels (MJ Surplus)	Resources	1.19E-04	200

The final scores for comparing the CO_2 recovery with ocean sequestration, first with the EDIP and next with the Eco-indicator, are displayed in Figures 6.10 and 6.11. The final scores for comparing CO_2 recovery with geological sequestration (EDIP *vs.* Eco-indicator) are displayed in Figure 6.12 for ocean sequestration and Figure 6.13 for geological sequestration. The results for mineral sequestration are displayed in Figures 6.14 (EDIP) and 6.15 (Eco-indicator).

The graphs display near similar trends. As observed from Figures 6.10 and 6.11, the biggest inverted peaks are found from ocean sequestration methods combined with chemical absorption with 98% CO_2 recovery rate, and highest peaks are observed from Pipe towed by Ship combined with the CO_2 recovery systems utilizing cryogenics (both 90% and 95% recovery rates). Differences are observed with the Pipe Towed by ship ocean sequestration option, that is, more negative scores are

generated with the EDIP whereas with Eco-indicator, the final scores mostly fall in the positive region. For the GLAD system, the final scores display all negative peaks with the EDIP and one positive peak with the Eco-indicator, when combined with cryogenics recovery method.

As for geological sequestration (Figures 6.12 and 6.13), the biggest inverted peaks are from both geological sequestration methods combined with chemical absorption with 98% CO_2 recovery rate, and highest peaks are observed from Pipe towed by Ship combined with the CO_2 recovery systems utilizing cryogenics (both 90% and 95% recovery rates). Also for both figures, the least inverted peak comes from combining cryogenics recovery (90% efficiency rate) with both EOR and ECBM.

Just as expected, the graphs in Figures 6.14 and 6.15 exhibit nearly the same patterns. The lowest peaks (negative final scores) come from combining chemical absorption with mineral sequestration methods 1, 2 and 5; and the highest peak all come from method 3. Various combinations of the CO_2 recovery systems with method 4 all display reasonable inverted peaks with both the EDIP and Eco-indicator.

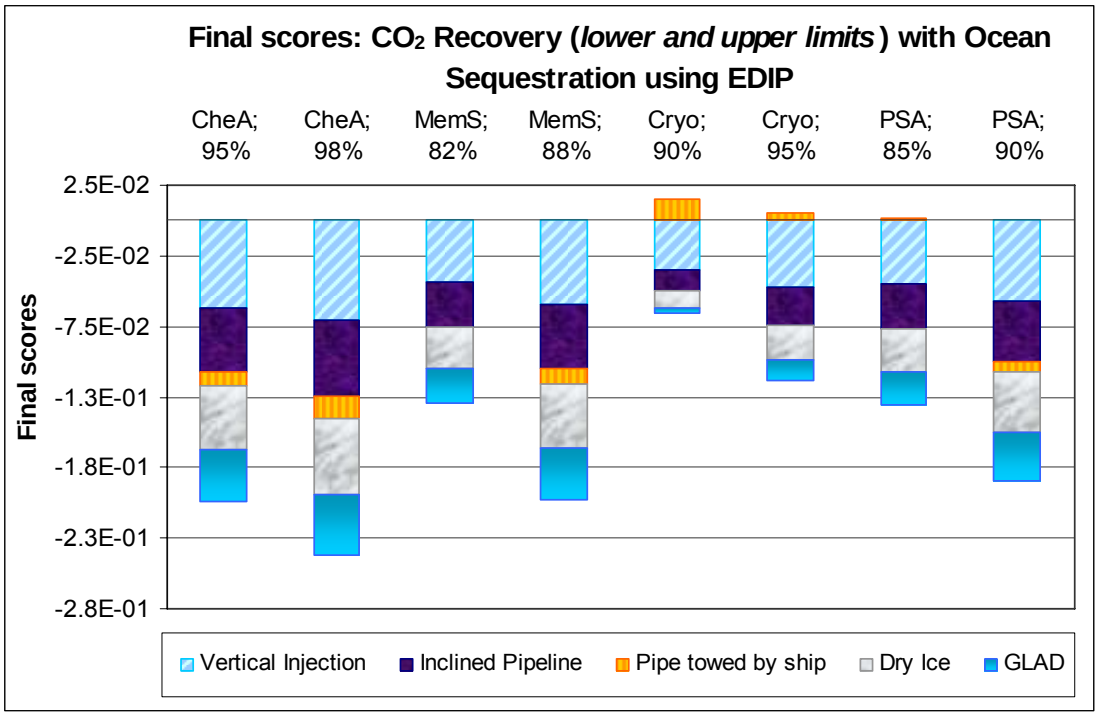

Figure 6.10. CO_2 recovery with ocean sequestration using EDIP

Note: CheA = Chemical Absorption; MemS = Membrane Separation; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

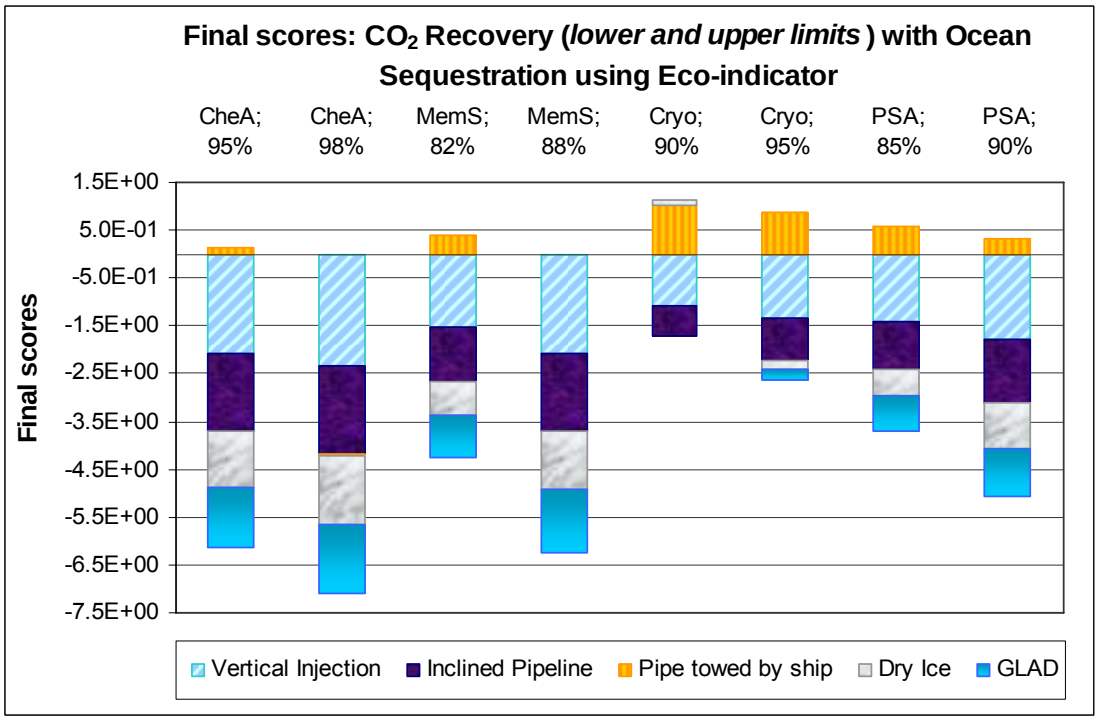

Figure 6.11. CO_2 recovery with ocean sequestration using Eco-indicator

Note: CheA = Chemical Absorption; MemS = Membrane Separation; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

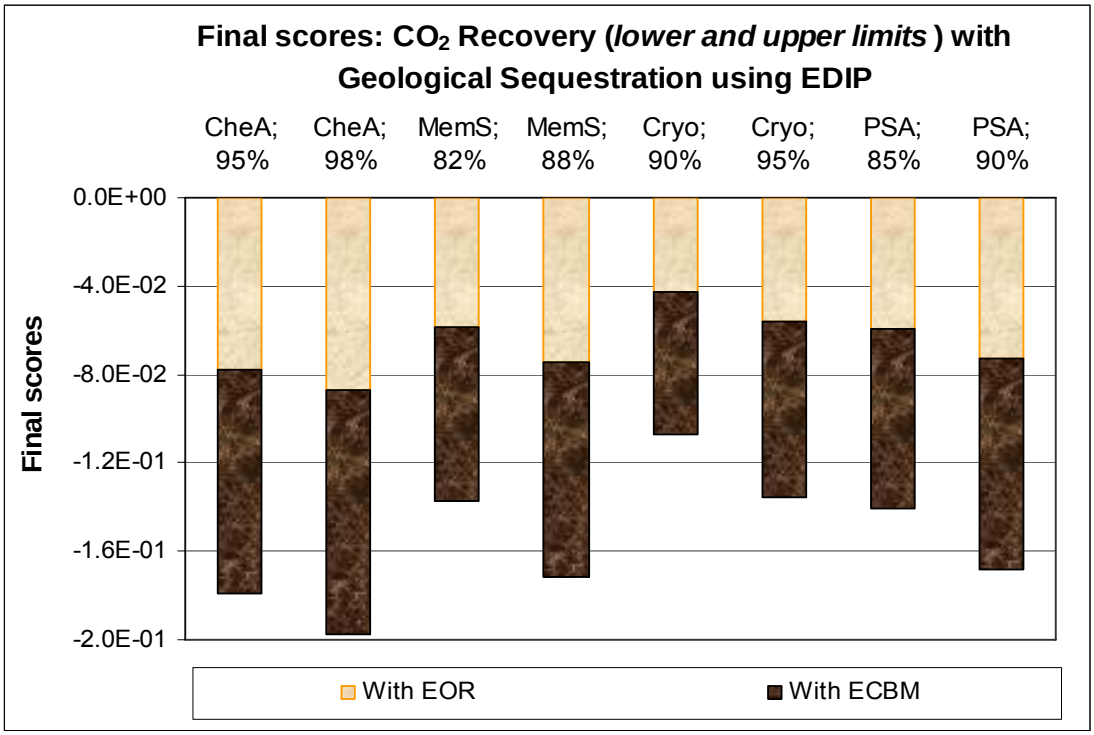

Figure 6.12. CO_2 recovery with geological sequestration using EDIP

Note: CheA = Chemical Absorption; MemS = Membrane Separation; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

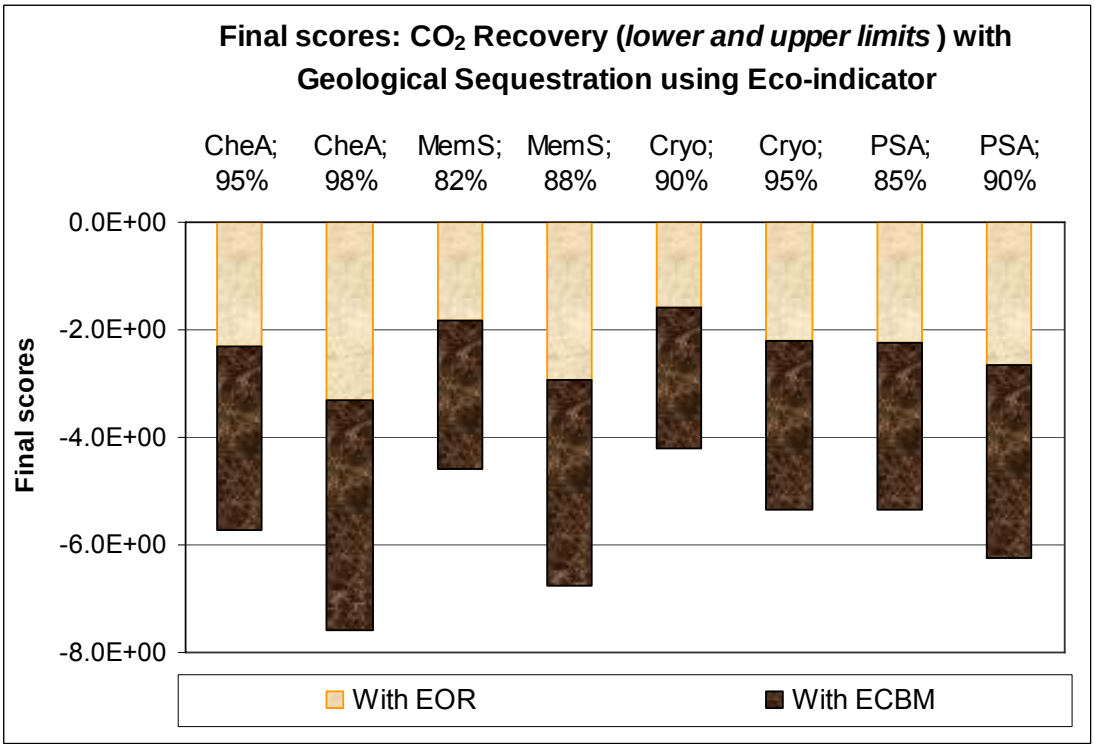

Figure 6.13. CO_2 recovery with geological sequestration using Eco-indicator

Note: CheA = Chemical Absorption; MemS = Membrane Separatoin; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

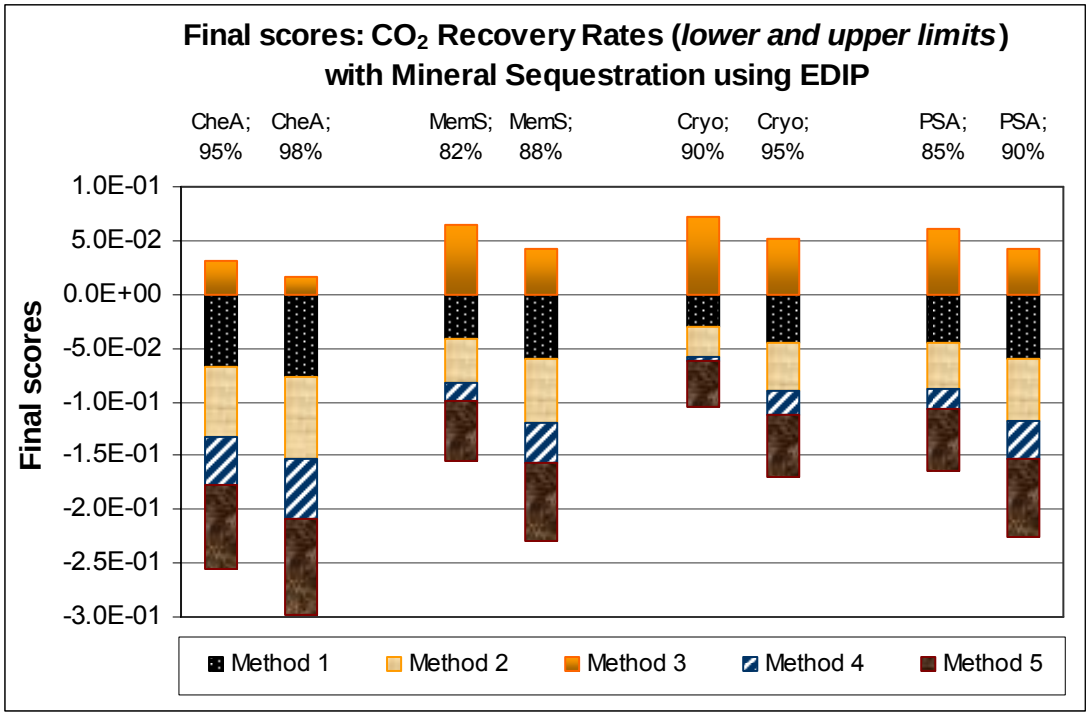

Figure 6.14. CO_2 recovery with mineral sequestration using EDIP

Note: CheA = Chemical Absorption; MemS = Membrane Separatoin; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

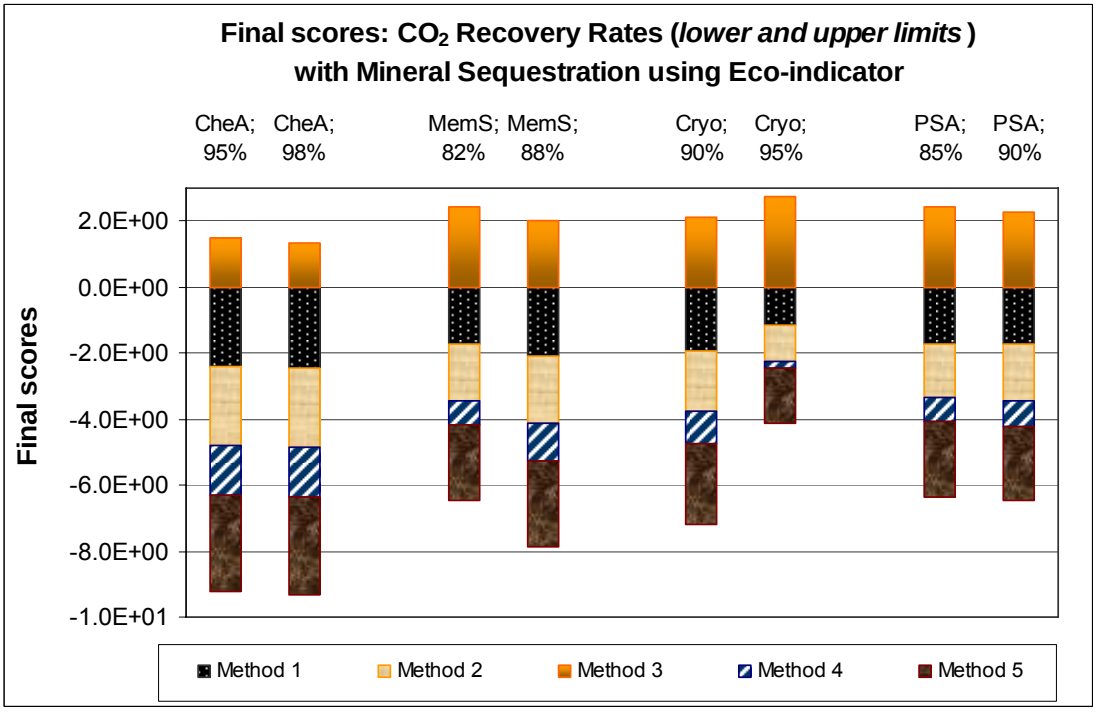

Figure 6.15. CO_2 recovery with mineral sequestration using Eco-indicator

Note: CheA = Chemical Absorption; MemS = Membrane Separatoin; Cryo = Cryogenics; PSA = Pressure Swing Adsorption

The three pairs of figures – 6.10 and 6.11, 6.12 and 6.13, and finally, 6.14 and 6.15 – demonstrate the application of a mid-point (EDIP) and end-point (Eco-indicator) impact assessment methodology. Mid-points are considered as a point in the cause-and-effect chain of an impact category, at which characterization factors of potential impacts are calculated to reflect the relative damage caused by air emissions, wastewater generated or the amount of resources consumed (Bare et al., 2000). The set of impact assessment results in Chapter 5 were generated based on this concept, where the mid-point indicators were in the form of CO_2-eq (for Global Warming), SO_2-eq (Acidification), etc.

End-points are the actual damages caused by the environmental loads. For instance in the case of Acidification, the end-points are the actual impacts that are caused by the protons released into the environment, that is, fish death due to the acidification of lakes (Bare et al., 2000).

In the EDIP (Hauschild and Wenzel, 1998), the category indicators are GWP, Acidification, Human Toxicity, Euthrophication, Ecotoxicity, Wastes and Resources. In Eco-indicator (Gooedkoop and Spriensma, 2001), the category indicators are DALY (Disability Adjusted Life Years) modelling the effect on human health, PDF (Potentially Disappeared Fraction) modelling the ecosystem quality and Resource damage quantifying the depletion of primary resources. While the overall trends in the three sets of results are similar, the differences in magnitude of the category indicator results demonstrate the variation between the mid-point (EDIP) and end-point (Eco-indicator) approach to life cycle impact assessment.

6.3 Sequestration Effectiveness

Sequestration effectiveness is measured by the final percentage of CO_2 that is prevented from entering the atmosphere. The *Sequestration Effectiveness*, or the percentage reduction of CO_2, is calculated using the simple formula:

$$\frac{CO_2^{(1)} - [\, CO_2^{(2)} + CO_2^{(3)} \,]}{CO_2^{(1)}} \times 100\% \qquad \ldots\ldots\ldots\ldots\ldots (v)$$

$CO_2^{(1)}$ = Total CO_2 emissions sequestered from the power plant

$CO_2^{(2)}$ = Total CO_2 emissions due to the energy requirements of the CO_2 recovery technology

$CO_2^{(3)}$ = Total CO_2 emissions due to the energy requirements of the CO_2 sequestration system (excluding the final amount of CO_2 sequestered)

For an ideal case of capturing and sequestering the entire amount of CO_2 generating from the power plant, *without* producing any additional greenhouse gases, the sequestration effectiveness will be calculated as 100%. The sequestration effectiveness results, for the *lower and upper limits* of CO_2 recovery combined with sequestration systems, are displayed in Table 6.6 (for ocean and geological sequestration) and 6.6 (for mineral sequestration).

Table 6.6. Sequestration Effectiveness results for all combinations of ocean and geological sequestration

CO_2 Recovery Technologies and Recovery Rates		OCEAN				GEOLOGICAL		
		Vertical Injection	Inclined Pipeline	Pipe towed by ship	Dry Ice	GLAD	With EOR	With ECBM
Chemical Absorption	**95%**	83%	75%	67%	82%	69%	83%	88%
	98%	87%	78%	71%	86%	72%	87%	92%
Membrane Separation	**82%**	70%	63%	57%	68%	59%	73%	77%
	88%	76%	69%	62%	75%	64%	78%	83%
Cryogenics	**90%**	74%	67%	59%	72%	61%	75%	80%
	95%	82%	74%	66%	80%	67%	82%	87%
Pressure Swing Adsorption	**85%**	72%	65%	58%	70%	60%	74%	78%
	90%	78%	70%	63%	76%	65%	79%	84%

Note. All results are based on: Functional Unit = 1 MWh from the coal-fired power plant and the generation of 950 kg-CO_2 per MWh

From Table 6.6, it can be seen that the highest sequestration effectiveness comes from combining chemical absorption method to recover CO_2 combined with the geological sequestration option along with ECBM, that is, 88% (*lower limit*) and 92% (*upper limit*). The next two highest sequestration effectiveness results are given by the same CO_2 recovery method with EOR (also geological sequestration) and Vertical Injection (ocean sequestration). Both display sequestration effectiveness results of approximately 83%-87%. Geological sequestration options with ECBM and EOR, and the Vertical Injection option combined with Cryogenics also display acceptable results. A sequestration effectiveness of 80%-87% is achieved for ECBM and, approximately 75-82% for both EOR and Vertical Injection.

With membrane separation, the two geological sequestration displays reasonable scores ranging from 73% to 83%. Vertical Injection with membrane separation displays results of 70-76%. The three sequestration options achieve results ranging from 72% to 78% when combined with the *lower* CO_2 recovery limits of PSA method, and 78% to 84% when combined with the *upper* CO_2 recovery limits of PSA method.

The Dry Ice method also displays acceptable sequestration effectiveness results when combined with the chemical absorption and cryogenics method. The results are 82-86% with chemical absorption and 72-80% with cryogenics. Dry Ice combined with the other CO_2 recovery methods show results ranging between 68% and 76%. Another ocean sequestration method, Inclined Pipeline, display sequestration effectiveness results of 75-78% with chemical absorption, approximately 67-74% with cryogenics fractionation, and 63-70% for the others.

As for the GLAD system, only the combination of chemical absorption with 98% CO_2 recovery efficiency has achieved results of 69-72% sequestration effectiveness, the rest of the results fall below 68%. The lowest score for GLAD is displayed when combining the method with membrane separation (82% CO_2 recovery efficiency), that is, a results of 59% sequestration effectiveness. Compared to the rest of the CO_2 sequestration options, the Pipe Towed by Ship option displays the lowest sequestration effectiveness results. They are: 67-71% with chemical absorption, 57-62% with membrane separation, 59-66% with cryogenics and finally, 58-63% with the PSA method.

Table 6.7. Sequestration Effectiveness results for all combinations of mineral sequestration

CO_2 Recovery Technologies and Recovery Rates		MINERAL SEQUESTRATION				
		Method 1	Method 2	Method 3	Method 4	Method 5
Chemical Absorption	**95%**	90%	90%	83%	89%	91%
	98%	96%	96%	93%	95%	97%
Membrane Separation	**82%**	72%	72%	50%	67%	75%
	88%	81%	81%	65%	77%	83%
Cryogenics	**90%**	79%	78%	65%	75%	80%
	95%	89%	89%	82%	87%	90%
Pressure Swing Adsorption	**85%**	75%	75%	56%	70%	77%
	90%	83%	83%	69%	80%	85%

Note. All results are based on: Functional Unit = 1 MWh from the coal-fired power plant and the generation of 950 kg-CO_2 per MWh

With reference to Table 6.7, the highest potential of CO_2 that can be sequestered successfully is achieved by combining chemical absorption to recover CO_2 with mineral sequestration method 5. Up to 97% sequestration effectiveness is accomplished with the recovery efficiency of 98%. With the same CO_2 recovery technology, methods 1 and 2 both achieved sequestration effectiveness results of 90-96%; and methods 3 and 4, 83-93% and 89-95% respectively. When combined with the other three CO_2 recovery systems, method 5 displays sequestration effectiveness results ranging from 75% (membrane) to 85% (PSA).

The lowest sequestration effectiveness scores are generated when mineral sequestration method 3 is combined with membrane separation (50-65%), PSA (56-69%) and cryogenics separation with CO_2 recovery rate of 90%. Method 4, which

utilizes serpentine, results in 67% sequestration effectiveness in combination with membrane separation; and methods 1 and 2 (both using olivine) results in 72% each with the same CO_2 recovery technology. The rest of the results are in the range of 75% to 89%.

CHAPTER 7

Conclusions and Recommendations

CHAPTER 7

Conclusions and Recommendations

7.1 Overview

This chapter is categorized into the following:

i. Overview of LCA – merits and limitations

ii. Overview of CO_2 sequestration – merits and limitations

iii. Suggestions for other low CO_2 emission power generation systems

iv. Conclusions

v. Recommendations

CO_2 recovery systems have already been applied in industry for many years and their implementations, developments and economical considerations were evaluated and reported by others (Dijkstra and Jansen, 2004; Audus, 2000; Göttlicher and Pruschek, 1997). Therefore the four CO_2 recovery technologies will not be reviewed in this last chapter.

7.1.1 Overview of LCA

7.1.1.1 Merits

One of the key advantages of using LCA is that it allowed a comprehensive analysis for the separate (individual) systems, and also, a complete final comparison of the entire system (Khoo and Tan, 2006a; 2006b; 2006c). This provided a systematic approach in determining the most environmentally suitable combination of options, for CO_2 recovery and sequestration, based on a particular Functional Unit (1 MWh).

In LCA, the mandatory steps are:

1. Selection of impact categories, category indicators and methods, e.g., EDIP (described in chapter 2)
2. Goal and scope definition, and objectives of the study (presented in chapter 4)
3. Assignment of LCI results (presented in chapter 4)
4. Calculations of impact results (characterization), which was presented in chapter 5

And the optional steps are:

5. Calculating the impact results relative to reference values (Normalization) and grouping into a final score (Weighting). This was presented in chapter 6.
6. Sensitivity Analysis for further comparisons and interpretations (also in chapter 6).

All six of these LCA steps were carried out, in line with the SETAC "code of practice" for LCA (Consoli, 1993), as well as, in accordance with the ISO 14040 standardized framework for LCA.

LCA employs a holistic systems approach that allowed the roles of CO_2 recovery and sequestration systems to be evaluated not just based on their merits of preventing global warming, but also along with the total accumulations of other potential pollutants and their consequential damages to human health and environment. The EDIP method that was applied for generating the impact assessment results is widely recognized and accepted by LCA experts and practitioners worldwide (Hauschild and Wenzel, 1998), which adds to the strength of the evaluation.

LCA provides the data to allow informed environmental management. It can be used to assess the interactions with the environment associated with a series of processes or activities within a system. The LCA investigation allowed the environmental benefits and drawbacks of the chain of processes involved to be carefully reviewed, before a real life large-scale sequestration plant is built. Problematic areas, where the environmental impacts turned out to be larger than expected, were able to be brought to attention. In this manner, the case of "shifting the burden" in the process of solving a particular environmental issue – while concurrently creating another elsewhere – is avoided.

Based on a life cycle approach, results for Sequestration Effectiveness, based on CO_2 emissions alone, were also carried out. Finally, the some key benefits of LCA that were identified are as follows:

- LCA is a multidisciplinary and flexible tool. Any new types of new technologies, or process changes, can be incorporated within the study.
- LCA allows the communication and translation of complex systems into simpler forms. The different types of impacts generated from the chain of processes within a system can be successfully translated into single scores.
- LCA is becoming more recognized and accepted globally for its powerful use and the ability to trace and compare the environmental outcomes of various products or processes.
- A holistic tool which translates, as complete as possible, how human activities interact with the environment
- The LCIA results can provide information for decision making at all levels – technical, administrative and/or top management.
- Updates of new information are possible to be included in any LCA model.

7.1.1.2 LCA Limitations

There are three main drawbacks in the LCA method used. The first lies in data quality and the second is the Weighting method. Finally, an impact category catered towards the effects of marine life due to the presence of CO_2 in the ocean is yet to be developed.

Throughout the research work, the LCI data covers mainly: coal mining, transportation and electricity generation from the coal-fired power plant; energy consumption for the recovery technologies and sequestration processes involved, transport pollution, the amount of CO_2 sequestered or stored, and finally, CO_2 leakage rates. Other types of data were unavailable. These will be explained in greater details in sub-section 7.1.2.2.

Secondly, the method of Weighting in impact categories according to ISO 14042 on Life Cycle Impact Assessment (LCIA) is particularly difficult to be agreed upon on a global scale, as they have to consider a wide range of issues – environmental imperatives and regulations, government, expert opinions and any other social issues (Schmidt and Sullivan, 2002). The Weighting values used for different impact categories can vary from "1.1" for Wastes/Resources or "1.3" for GWP/Acidification to "2.8" for Human Toxicity to Air (SimaPro, 2005). This makes the determination of Weights a controversial issue in LCIA, and weighting methods have been shown to be subjective in nature (Bare et al., 2000). Despite intensive development worldwide, few attempts have been made hitherto to systematically present the theoretical bases for the weightages used in the final stage of the impact assessment method.

The final key limitation of the LCIA method is that the impacts on marine life due to the release and accumulation of CO_2 in the ocean is not included in the EDIP or Eco-indicator (Gooedkoop and Spriensma, 2001; Hauschild and Wenzel, 1998). The possible impacts or damages that can be caused by the "dumping" CO_2 in the ocean have raised many public concerns. Kita and Ohsumi (2004) reported that the possible biological impacts can be categorized into acute and chronic impacts. However, quantitative damages on ocean seafloor or marine lifeforms are yet to be publicly available. The experiments and analysis required to predict these kinds of impacts can turn out to be quite a complex task (Ishimatsu at al., 2004; Poremski, 2004).

7.1.2 Overview of CO_2 Sequestration

7.1.2.1 Merits

Although the science of CO_2 sequestration – ocean, geological and mineral – is still relatively new, numerous renowned scientists, engineers and researchers have regarded them as promising solutions to mitigate global warming (e.g., O'Connor et al., 2005; Herzog et al., 2001; Nihous, 1997; Ozaki, 1997; Millero, 1995). Especially for the case of geological sequestration, which offers relatively safe storage of CO_2, as well as, the economical and environmental benefits of the recovery of useful resources (oil and natural gas). Coalbeds have the potential to store vast quantities of CO_2, and at the same time the injected greenhouse gas can be used to enhance the recovery of methane. Accordingly, ECBM is viewed as a promising method for mitigating CO_2 emissions from coal-fired power plants while providing significant economic benefit (Tamabayashi et al., 2004).

As for the case of EOR, the injection of CO_2 underground with oil recovery is reported to be a proven technology (Agustsson and Statoil, 2004; Holloway, 1997), where pipeline engineering knowledge exists to allow the transfer of compressed CO_2 from its source to the storage site (Svensson et al., 2003). In fact, petroleum industries in the U.S. has for many years been injecting CO_2 in geological formations to improve oil recovery (Aycaguer et al., 2001). A second advantage for the underground storage of CO_2 lies in its large storage capacity. The IEA Greenhouse R&D Programme estimated that the global storage capacity of oil and gas reservoirs is at least 660 Gt CO_2 (Riemer, 1996).

In fact, geological storage of CO_2 is ongoing in three industrial-scale projects: the *Sleipner* project in the North Sea, the *Weyburn* project in Canada (Figure 7.1 below) and the *In Salah* project in Algeria (IPCC, 2006).

Figure 7.1. *Weyburn* EOR project

The idea for the long-term storage of anthropogenic CO_2 in the ocean had been proposed as early as 1977 (Marchetti, 1977). This idea was further pursued by scientists and engineers in U.S., Europe and Japan (e.g., Caldeira et al., 2001; Herzog et al., 2001; Kajishima et al., 1995; Ozaki et al., 1995). The ocean is being viewed as the largest potential repository of CO_2, and already contains nearly 40,000 GtC of the greenhouse gas (Turkenburg, 1997). The engineering knowledge required for hanging or suspended pipes, inclined pipelines and ocean tankers required to deliver CO_2 to the ocean storage area is reported to be technologically possible and feasible (Aspelund et al., 2004; Sasaki, 2004; Golomb, 1997).

Particularly for depths below 3000 m, liquid CO_2 will be denser than the surrounding seawater and CO_2 lakes will form at sea floors. This means that ocean sequestration sites must be carefully selected. Caldeira and Wickett (2005) have investigated various locations that are suitable for ocean sequestration projects, particularly for distances over land to water that is at least 1-3 km deep. This is shown in Figure 7.2.

However, there are a few marine environmentalists and oceanographers who may disagree entirely with the concept (as will be discussed in the next section) therefore each potential site would need to be evaluated prior to deployment.

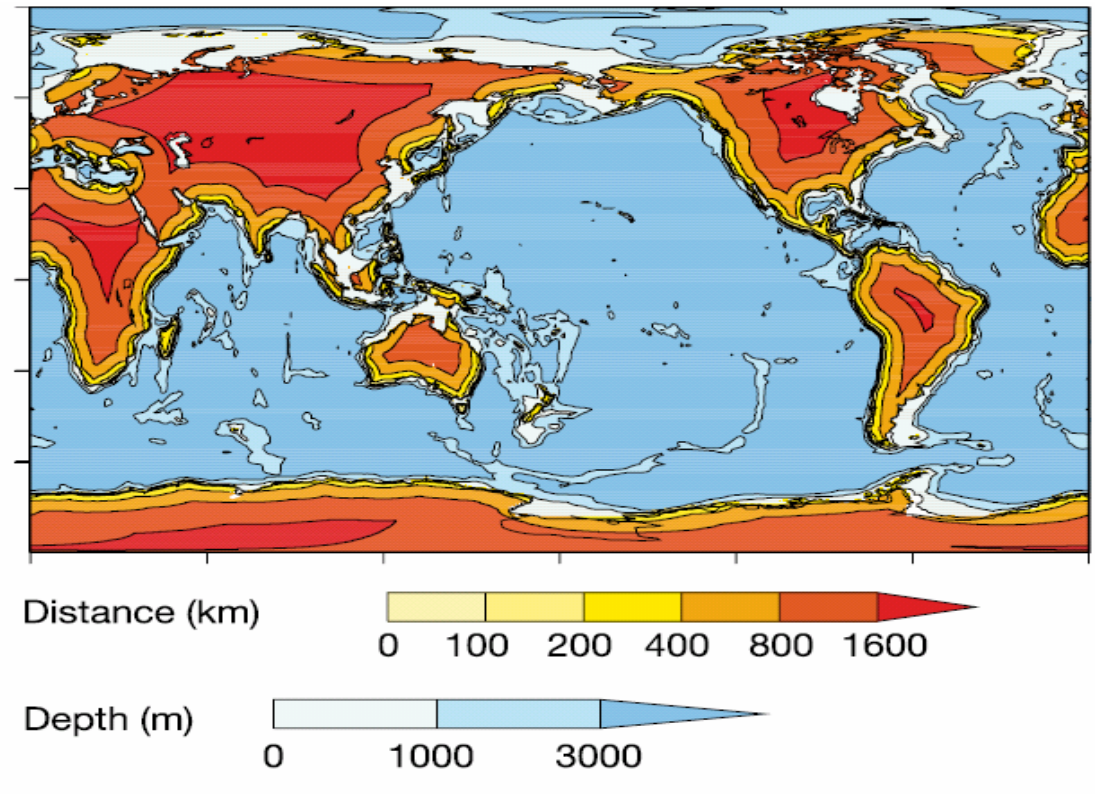

Figure 7.2. Potential locations for CO_2 sequestration

(Land areas with the lightest colors would be the most cost effective locations for CO_2-injection operations)

Finally, mineral sequestration, which attempts to mimic the weathering of rocks for the transformation of CO_2 into calcium or magnesium carbonates (Park et al., 2003), offers the advantage of being thermodynamically stable for millions of years (Voormeij and Simand, 2003; Zevenhoven and Kohlmann, 2001). Moreover, mineral feedstocks are widely available. Olivine deposits are spread across North Carolina (O'Connor et al., 2004) and wollastonite be found in Willsboro (O'Connor et al., 2005). Commercial applications for the carbonated rocks include construction material (bricks) or as use for pavements.

7.1.2.2 Limitations

It should be highlighted that the main objective of the study is to use LCA to make scientific comparisons, rather than to suggest the application of CO_2 sequestration as the final answer to mitigate global warming. No single solution should be promoted, and further investigations are necessary to determine the safety of any sequestration efforts, especially for ocean sequestration.

The ocean is a complex and dynamic system, and the site and location for CO_2 ocean sequestration should be selected very cautiously, taking into consideration depths, currents and ocean carbon cycles (Schenck, 2004). Recently, several letters petitioning against the proposal of "dumping" CO_2 into the ocean has caused the prevention of a field experiment to sequester CO_2 into the ocean along the coastal areas of Hawaii (deFigueiredo, 2003).

For CO_2 ocean sequestration, the risks of marine life have to be appropriately investigated. This includes the reduction in seawater pH near the point of injection or disposal and their effects on marine organisms. Golomb et al. (1992) suggested that other impacts of deep-sea CO_2 disposal could include interference with feeding patterns of swimming creatures and burial of benthic organisms by CO_2-hydrate on the sea floor. Preliminary tests have shown that "some impacts are inevitable around the release point (of CO_2), but their severity will depend on the release technology (applied)" (Herzog et al., 1996). This area of research is still wanting in terms of real-world verification and was left out of the LCA investigation.

Geological sequestration is not altogether considered "risk free". Storage in geological formations will not lead to perfect retention of CO_2 forever and the issue of leakage rate has also been a concern for public safety (Holloway, 1997). An underground reservoir as an injection site (as with EOR and ECBM) may experience large pressure differences, causing the slow and gradual migration of CO_2 upwards to take place (Hepple and Benson, 2002). Also for geological sequestration, the possibilities of pipeline corrosion or leaks from long distance pipeline transportation should be taken into account. However, actual data regarding these matters were unavailable and were not incorporated within the LCI results.

The third and final sequestration option is the storage of CO_2 as mineral rocks. Mineral sequestration will only make sense if the total environmental impacts arising form the carbonation processes themselves do not exceed the avoided atmospheric release of CO_2 (i.e., prevention of global warming). Presently, the amounts of energy or heat necessary to activate some of the minerals are extremely high, principally for the case of serpentine. Apart from not being economically viable, the mineral processing plant itself may turn out to be yet another environmental threat. Furthermore, pollution arising from mineral mining, crushing and grinding – which were not included in the LCA – would have added to even greater environmental burdens.

Table 7.1 summarizes the issues pertaining to leakage rates, status, technology, safety and public acceptability of ocean, mineral and geological sequestration.

Table 7.1. Summary of CO_2 sequestration options: leakage rates, status, technology and social concerns

CO_2 Storage options	**Ocean**			**Geological**		**Mineral**
Potential Leakage rates	Less than 2000m	2000 to 3000m	At least 3000m	EOR	ECBM	Virtually none (Up to millions years of storage)
	High	Acceptable	Low	Low	Low	
Status and Technology	First proposed by Marchetti in 1977. Interests have spread to U.S.A, Europe and Japan. The technology for the transportation of compressed or liquid gasses by pipe already exists. Direct injection of CO_2 into the ocean has been claimed to be technically feasible. Ocean tanker transportation is possible, but not without additional pollution.			Underground storage of CO_2 is already an on-going field and considered to be technologically mature. The engineering capability for long distance pipelines transportation for compressed or liquid gasses has also been a proven technology. To date, the sources of CO_2 for EOR/ECBM operations are yet to be from power plants.		First mentioned by Seifritz in 1990. Presently experiments for mineral carbonation are carried out at the Albany Research Center. The energy required for Standard Pre-treatment and Activation (to necessitate 100% conversion of the gas to mineral rocks) are highly energy intensive.
Safety and public concerns	Letters petitioning against the "dumping" CO_2 into the ocean has prevented a field experiment for ocean sequestration in Hawaii to take place. Some of the concerns are lack of information on seawater change (pH) and the potential impact on marine life.			This is seen as an approachable concept, with additional benefits of resource recovery. The main concerns are the possibilities of pipeline ruptures, human safety and leakage rates, as discussed by many research scientists.		The advantage of mineral CO_2 sequestration lies in the thermodynamic stability of the formed carbonate rocks, which are considered to be permanent and inherently safe.

Apart from coal-fired power production in conjunction with CO_2 recovery and sequestration, the following sections give two more suggestions for reducing CO_2 levels: i) IGCC power generation, ii) fuel cell technology.

7.1.3 IGCC power generation

To address the global environmental impacts caused by excessive CO_2 emissions, new coal utilization technologies are being developed. One of the more promising of these is the Integrated Gasification Combined Cycle (IGCC) system for power generation. In contrast to the pulverized-coal power plants, the IGCC technology uses less water, generates less solid waste, and can concentrate carbon dioxide emissions, making CO_2 easier to capture and store (Ordorica-Garcia et al., 2006).

IGCC technology consists of two main stages. The first is called coal gasification, which uses coal to create a clean-burning gas (syngas). The most efficient way to use the energy contained in the gas is to drive a gas turbine with the gas and use the hot combustion gas for steam generation in a boiler. The second stage employs what is known as a combined-cycle, a highly efficient method of producing electricity. A typical IGCC system is shown in Figure 7.3 below.

IGCC power plants use less coal and produce much lower emissions of carbon dioxide than conventional power plants. An IGCC demonstration plant with an operating efficiency of 45% is reported to emit up to 740 kg-CO_2 per MWh (Boehme and Krey, 2005). At present, the cost of an IGCC plant is 15 to 20% higher than that of conventional coal-fired power plants.

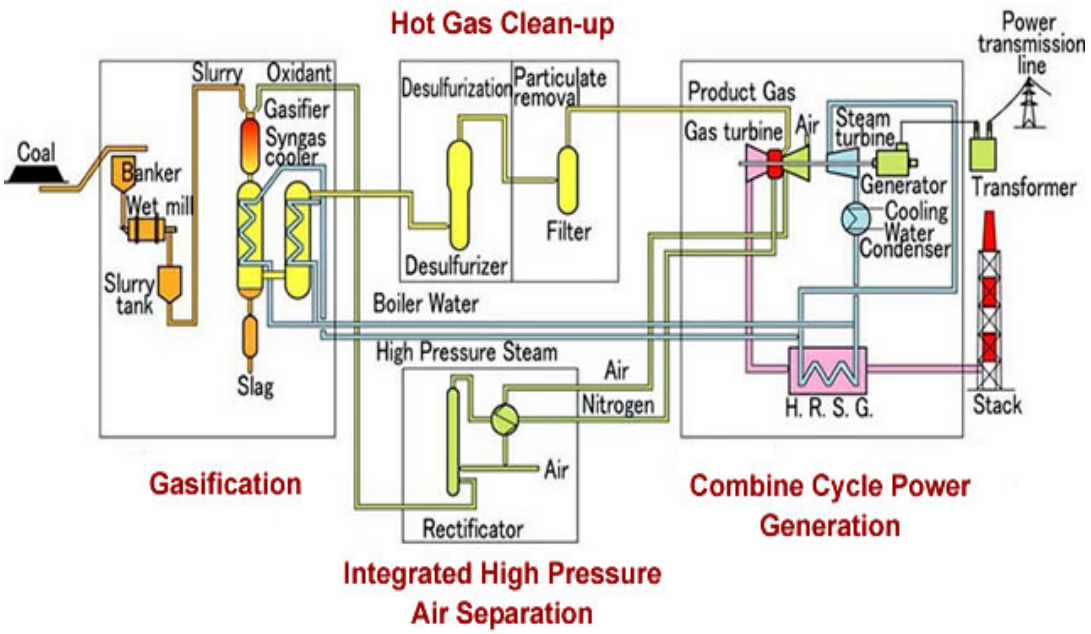

Figure 7.3. Typical IGCC electrical generation system

7.1.4 Fuel Cell technology

Fuel cells have the potential to meet high energy demands with low CO_2 emissions. The technology employed by fuel cells is based on electrochemical energy conversion. The working principle is carried out by the combination of two electrodes, the cathode and anode. The reactions that produce electricity take place at the electrodes. Since fuel cells create electricity chemically, rather than by combustion, they are not subject to the thermodynamic laws that limit a conventional power plant.

By the use of hydrogen or natural gas as the source of energy, fuel cells are often promoted as being future clean energy generation systems. Fuel cells have the potential to power laptops, handphones, cars, buildings or homes (Bischoff, 2006).

A small-scale prototype molten carbonate fuel cell (MCFC) power generator is reported to emit 486 kg CO_2 per MWh (Raugei et al., 2005). However, fuel cell technologies are still in the early stages of research and development. The main barriers to implementing large-scale fuel cell power generating systems include the need for lower cost equipment and more particularly efficient hydrogen production processes.

7.2 Conclusions

Three interlinked stages were studied for the objective of reducing the amount of CO_2 emissions in the atmosphere. In Stage 1, coal-fired electricity production was described. In Stage 2, four CO_2 recovery technologies were presented: chemical absorption, membrane separation, cryogenic fractionation and pressure swing adsorption (PSA). Finally in Stage 3, five proposed ocean sequestration options (Vertical Injection, Inclined Pipeline, Pipe Towed by Ship, Dry Ice, GLAD), two geological sequestration systems (EOR and ECBM), and finally, five mineral sequestration process routes were described. LCA was applied to investigate the three stages, first as separate sub-systems, and next as an undivided chain of processes (whole system).

The EDIP method was applied to generate eight environmental impact results: Global Warming Potential, Acidifcation, Human Toxicity to Air, Human Toxicity to Water, Eutrophication, Ecotoxicity, Wastes and Resources. In the first analysis, the *lower limits* of the CO_2 recovery efficiencies were estimated to be 95%, 82%, 90% and 85% for chemical absorption, membrane separation, cryogenics and PSA respectively. The results illustrated the quantified environmental consequences of each individual

system due to the amount of CO_2 that was successfully recovered or sequestered, the amount of CO_2 that was released (un-recovered or un-sequestered), SOx and NOx gases, heavy metal emissions, wastewater, solid waste, and resource consumption and recovery.

Next, the EDIP was again applied to generate the Final Scores of a total of 48 combinations of CO_2 recovery and sequestration systems (4 types of recovery systems multiplied by 12 sequestration options). The initial results showed that the least environmental impacts stems predominantly from the two geological sequestration methods. The Final Scores for EOR and ECBM showed promising results stemming from two benefits – the prevention of both Global Warming Potential and resource depletion. This result was further verified by a hypothesis test to be *'extremely significant'* (*t-test* = 472.8).

For ocean sequestration, the highest environmental benefits stem from three combinations. First of all, Vertical Injection, followed by Inclined Pipeline – both combined with chemical absorption. The Dry Ice option achieved satisfactory results only when it is combined with highly efficient CO_2 recovery methods. Further t-test results also verified the '*high significance*' of these conclusions (*t-test* = 30.08).

The other two options, Pipe Towed by Ship and GLAD lacked the potential to successfully sequester large amounts of CO_2.

For mineral sequestration, methods 1, 2 (both utilizing olivine) and 5 (wollastonite), offered quite promising results for the prevention of global warming. Method 3

(utilizing serpentine), demanded rather high energy requirements in the carbonation processes and tend to result in higher levels of CO_2 emissions instead of its prevention. However, the conclusions for mineral sequestration did not carry high significance (*t-test* = 2.42).

Sensitivity Analysis was performed to test the higher efficiencies of the CO_2 recovery systems: 98% for chemical absorption, 88% for membrane separation, 95% for cryogenics and finally, 90% for PSA. Following this, most of the final scores for all the combinations of CO_2 recovery and sequestration systems improved from approximately 15% to over 50% for both ocean and mineral sequestration, and approximately 10%-25% for geological sequestration.

Sensitivity Analysis was also used to test: different levels of power plant emissions (from 950 to 970 and 990 kg CO_2/MWh); different EDIP weights (Med, Low, High) and finally; for comparing any differences in the final results generated when the EDIP or Eco-indicator impact assessment method is used.

The different levels of CO_2 emissions (950, 970, 990 kg) from the power plant hardly had any impact on the Final Scores – only 2-4% changes were observed. As for the changes in Weights, the Final Scores dropped by around 21% to 43% for "Med" to "Low" and increased over 50% for "Med to "High" for ocean sequestration; and dropped by 16-26% for "Med" to "Low" and increased 50-55% for "Med" to "High" for geological sequestration. In mineral sequestration, most of the fluctuations are an average of 50%, except for Cryogenics combined with method 4, which experienced

more drastic changes. The final comparison – EDIP vs. Eco-indicator – resulted in pairs of graphs for all three sequestration options which displayed very similar trends.

When the Weights were raised for Human Toxicity (alone), the Final Scores hardly changed. However, when high Weights were placed for GWP, the Final Scores improved by approximately 50-60% for most of the ocean and geological sequestration options, and over 100% for Pipe Towed by Ship and GLAD. Large jumps in Final Scores were also observed for Mineral Sequestration.

Sequestration Effectiveness results were calculated (based on CO_2 emissions only), for all four combinations of the *lower and upper limits* of the CO_2 recovery methods with the seven sequestration options. The results were: 77-92% (ECBM), 73-87% (EOR), 70-87% (Vertical Injection), 68-86% (Dry Ice), 63-78% (Inclined Pipeline), 59-72% (GLAD) and finally, 57-71% (Pipe Towed by Ship).

In summary, the project successfully achieved the following objectives (as listed out in chapter 1):

- the series of processes involved for mitigating CO_2, from a cradle-to-grave perspective, was studied and investigated
- the environmental consequences of the processes involved were compiled and quantified
- existing and proposed technologies were successfully compared
- larger than expected environmental burdens arising from any part of the system were able to be highlighted

- the combination of systems was evaluated based on a holistic approach, that is, the environmental results took into account every other necessary environmental impacts (Acidification, Human Toxicity, Resources, Ecotoxicity, etc) and not just Global Warming alone.

7.3 Recommendations (Future work)

Based on the overview and conclusions, the future work will focus on: the impacts of CO_2 in the ocean (acidity, marine life and movement and chemistry changes), further developments for geological and mineral sequestration, LCA data quality, Weighting values and finally, other types of power generation systems.

7.3.1 Impact of CO_2 on ocean acidity

There have been concerns about the decreasing ocean pH due to excessive CO_2 intakes. It was reported that the average pH of the oceans will fall by up to 0.5 units by 2100 if global emissions of CO_2 continue to rise at present rates (Royal Society of Chemistry, 2007). The acidification around the release point of CO_2 may be the most important impact. Further investigations should be made to estimate the cumulative effects of varying pH exposure and in future LCA systems should be combined with a model that predicts impacts on the ocean from the reduced pH.

7.3.2 Impact of CO_2 on marine life

Adding CO_2 into the ocean can harm marine organisms. Some of the expected phenomena may include reduced rates of calcification, reproduction, growth, circulatory oxygen supply and mobility. However, the chronic effects of direct CO_2 injection into the ocean on marine organisms or ecosystems over large ocean areas

and long time scales have not yet been studied (Ishimatsu at al., 2004; Poremski, 2004). Hard data on the exact damages of marine lifeforms are yet to be reported. It is recommended that experiments and analysis are performed to predict these kinds of impacts so that future LCA studies may include these effects as part of the LCIA results.

7.3.3 Tracking of CO_2 movements in ocean

The injection of a few $GtCO_2$ would produce a measurable change in ocean chemistry in the region of injection, whereas the injection of hundreds of $GtCO_2$ would produce larger changes in the region of injection and eventually produce measurable changes over the entire ocean volume (IPCC, 2006). Further experimental studies should be performed for tracking the movement of liquid CO_2 droplets in ocean currents, as well as, changes in ocean chemistry around the release site.

7.3.4. Further developments for geological sequestration

The storage of CO_2 in geological formations will not lead to perfect retention of the greenhouse gas as slow and gradual migration of CO_2 upwards can be expected (Holloway, 1997). The study of underground formations, including porosity, permeability, thickness, volume, etc. should be carried out. Particularly for ECBM, geologic heterogeneity is a primary consideration. Stratigraphy, structural geology, hydrodynamics, geothermics, coal quality and sorption capacity are fundamental parameters used to assess ECBM and CO_2 sequestration potential (Hepple and Benson, 2002). It is suggested that future work should focus around these parameters.

Another important aspect of geological sequestration should be on pipeline design. Just as there are standardized designs for natural gas admitted to pipelines, future

studies should focus on the minimum standards for 'pipeline quality' for the safe transportation of CO_2.

7.3.5. Further developments for mineral sequestration

Although the entrapment of CO_2 in minerals is considered to be very stable and environmentally safe, further investigations are needed for less energy intensive carbonation processes. It is also suggested that information on the pollution and waste created by mining and quarrying activities should be covered as part of the LCA.

7.3.6 Improvement of LCA inventory data

The quality and coverage of the LCI (inventory data) can be improved. In the report, the data covered were on: coal-fired power production (resources consumed and emissions to land, air and water), energy requirements of each CO_2 recovery technology, as well as, the energy requirements of each and every process involved in the 12 CO_2 sequestration systems. Other types of information were unavailable.

Information such as risks of pipeline corrosion, leakages or ruptures should be taken into account. These measures are important especially for the long-distance pipeline transportation of CO_2. Other additional emissions may come from ocean tanker boil-off. As mentioned for mineral sequestration, the pollution caused by mining and the extraction of minerals should also be included.

7.3.7 Globally accepted Weighting values

In LCIA, weighting methods have been shown to be subjective in nature (Bare et al., 2000). It was discussed that several methods exist to assign Weighting values for generating final impact assessment scores: society's willingness to pay, end-point measures (Huijbregts et al., 2005) and panel approach (Hofstetter, 1999; Soares et al., 2006), where the environmental priorities of all actors (scientists, policy makers, government and general public) are taken into account. Thus far, Weighing methods for LCIA has been developed based on specific regions (Europe or North America), and different values placed on Weights often result in a set of different Final Scores for an LCA system (as shown in section 6.2.3.2, Increased Weights for GWP). This calls for a need to adopt an international standardized procedure to develop and support Weighting values, especially for GWP, in a way that is globally accepted.

7.3.8 CO_2 recovery and sequestration with different power generation systems

Various clean or energy efficient technologies are being developed for electricity generation which emit considerably less CO_2 emissions. Two examples (e.g. IGCC power plant), were introduced earlier.

Another example is the NGCC (Natural Gas Combined Cycle) power plant, which can emit approximately half of the CO_2 emissions that are produced by a coal-fired power plant. Future LCA studies on CO_2 recovery and sequestration – or capture and storage – can be focused on these types of energy efficient power generation technologies.

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Appendix A

Characterization factors, Normalized values and Weights by the EDIP 97 method [Source: SimaPro, 2005]

Table A1. EDIP parameters for selected pollutants contributing to GWP

Global Warming Potential (CO_2-eq g)

Pollutant	Characterized factor	Normalize score	Weight
CO_2	1		
CO	2		
N_2O	320	1.15E-07	1.3
CH_4	25		
SF_6	24900		

Table A2. EDIP parameters for selected pollutants contributing to Acidification

Acidification (SO_2-eq g)

Pollutant	Characterized factor	Normalize score	Weight
SO_2/SOx	1		
Ammonia	1.88		
HCl	0.88	8.06E-06	1.3
NO_2/NOx	0.70		
HF	1.6		

Appendix A

Table A3. EDIP parameters for selected pollutants contributing to Human Toxicity to Air

Human Toxicity - Air (m^3/g)

Pollutant	Characterized factor	Normalize score	Weight
Arsenic	9.50E+06		
Cadmium	1.10E+08		
Cobalt	9.50E+03		
Copper	5.70E+02		
Dioxins	2.90E+10		
Iron	3.70E+04		
Lead	1.00E+08		
Manganese	2.50E+06	1.09E-10	2.8
Mercury	6.70E+04		
Nickel	6.70E+04		
Selenium	1.50E+06		
Silver	2.00E+05		
Titanium	1.80E+04		
Vanadium	1.40E+05		
Zinc	8.10E+04		

Table A4. EDIP parameters for selected pollutants contributing to Human Toxicity to Water

Human Toxicity - Water (m^3/g)

Pollutant	Characterized factor	Normalize score	Weight
Arsenic ions	3.70E+01		
Cadmium ions	2.80E+03		
Chlorides	0		
Fluorides	1.20E-02	1.69E-05	2.5
Metallic ions (unspecified)	3.23E+00		
Phenol	3.40E-02		

Appendix A

Table A5. EDIP parameters for selected pollutants contributing to Eutrophication

Eutrophication (NO_3-eq g)

Pollutant	Characterized factor	Normalize score	Weight
Ammonia	3.64		
Nitrates	1		
Cyanides	2.38	3.36E-06	1.2
N20 (Air)	2.82		
NOx (Air)	1.35		

Table A6. EDIP parameters for selected pollutants contributing to Ecotoxicity (Water Chronic)

Ecotoxicity (m^3/g)

Pollutant	Characterized factor	Normalize score	Weight
Acids	0.2		
Sulfides	3.3E+03	2.08E-05	2.3
Phenol	22		

Table A7. EDIP parameters for Wastes

Wastes (kg/kg)

Pollutant	Characterized factor	Normalize score	Weight
Solid Wastes (all types)	1.0	7.04E-04	1.1

Appendix A

Table A8. EDIP parameters for Resources

Resources (kg/kg)

Resource	Characterized factor	Normalize score	Weight
Coal*	0.00001		
Natural gas**	0.00005	1	1.1
oil***	0.000039		

*Coal in ground, hard, unspecified (MJ Surplus/kg)

**In ground, 30MJ per kg

***Oil, crude, in ground

Appendix B

Sample Calculation for impact assessment

The formula to calculate GWP for Vertical Injection (Stage 3) is expressed as:

$$\begin{aligned} GWP^{(\text{Vertical Injection})} = & \sum [CO_2{}^{(\text{liquefaction})} + CO_2{}^{(\text{ocean tanker})} + CO_2{}^{(\text{injection})} \\ & + CO_2{}^{(\text{leakage})} - CO_2{}^{(\text{sequestered})}] * \boldsymbol{1} \\ & + \sum [CO^{(\text{liquefaction})} + CO^{(\text{ocean tanker})} + CO^{(\text{injection})}] * \boldsymbol{2} \\ & + \sum [CH_4{}^{(\text{liquefaction})} + CH_4{}^{(\text{ocean tanker})} + CH_4{}^{(\text{injection})}] * \boldsymbol{25} \\ & + \sum [N_2O^{(\text{liquefaction})} + N_2O^{(\text{ocean tanker})} + N_2O^{(\text{injection})}] * \boldsymbol{320} \end{aligned}$$

……. *Eqn (1)*

Where:

$CO_2/CO/CH_4/N_2O^{(\text{liquefaction})}$ are the total greenhouse emissions generated due to the energy requirements for liquefying CO_2;

$CO_2/CO/CH_4/N_2O^{(\text{ocean tanker})}$ are the total greenhouse emissions generated from ocean tanker emissions;

$CO_2/CO/CH_4/N_2O^{(\text{injection})}$ are the total greenhouse emissions generated due to the energy requirements for compression + injection of CO_2

And:

$CO_2^{(\text{leakage})}$ = amount of CO_2 leakage to the atmosphere

$CO_2^{(\text{sequestered})}$ = amount of CO_2 sequestered by Vertical Injection

Note: ***1, 2, 25*** and ***320*** are the equivalent values of CO_2, CO, CH_4 and N_2O respectively.

(Refer to IPCC's *2001 Third Assessment Report* for detailed explanation)

Appendix B

(continued)

For LCA Stage 3, F.U = **1 MWh**, and CO_2 from power plant = 950-kg/MWh

⇒ The energy requirements are:

Liquefaction = 0.950 ton CO_2 * 120 kWh/ton = 114 kWh

Compression + Injection = 0.950 ton CO_2 * 40 kWh/ton = 38 kWh

From Table 4.2 (page 60):

Total CO_2 (liquefaction)	= 111.39 kg;	CO_2 (injection)	= 37.13 kg
Total CO (liquefaction)	= 0.0303 kg;	CO (injection)	= 0.010 kg
Total CH_4 (liquefaction)	= 0.1041 kg;	CH_4 (injection)	= 0.0347 kg
Total N_2O (liquefaction)	= 0.000505 kg;	N_2O (injection)	= 0.000168 kg

And CO_2 (sequestered) = 0.95*90% = 0.855 ton or 855 kg-CO_2

CO_2 (leakage) = 95 kg-CO_2

Finally, for Tanker transportation = 0.35 kg/(ton-km); for 0.95 ton and 100 km

CO_2 (ocean tanker) = 33.25 kg-CO_2

CO (ocean tanker) = CH_4 (ocean tanker) = N_2O (ocean tanker) = 0

Insert into *Eqn. (1)* ⇒ **GWP (Vertical Injection) = - 574.46 kg CO_2-eq** (Final Answer)

Appendix C

Hypothesis t-test calculations

Table C1. T-test for hypothesis 1

Parameters	Geological sequestration	Ocean and mineral sequestration	Remarks
$\sum x$	-0.564	-0.957	Total sum of all values
N	8	40	No. of values
x mean	-0.071	-0.024	Total value/N
$\sum x^2$	0.042	0.069	Sum of all x^2
$(\sum x)^2$	0.318	0.915	Square of ($\sum x$)
$\sum d^2$	2.23E-03	4.62E-02	$\sum d^2 = \sum x^2 - [(\sum x)^2 / N]$
σ^2	3.19E-04	1.19E-03	$\sigma^2 = \sum d^2 / (N-1)$
σ_d^2	6.95E-05		The variance of the difference between the means
σ_d	8.30E-04		Standard deviation
t-test result	**472.80**		Results are *Extremely Significant*

Table C2. T-test for hypothesis 2

Parameters	Chem. absoprtion with Vertical Injection, Inclined Pipeline and Dry Ice	All other ocean sequestration options	Remarks
$\sum x$	-0.154	-0.352	Total sum of all values
N	3	17	No. of values
x mean	-0.051	-0.021	Total value/N
$\sum x^2$	0.008	0.012	Sum of all x^2
$(\sum x)^2$	0.024	0.124	Square of ($\sum x$)
$\sum d^2$	1.56E-04	4.78E-03	$\sum d^2 = \sum x^2 - [(\sum x)^2 / N]$
σ^2	7.81E-05	2.99E-04	$\sigma^2 = \sum d^2 / (N-1)$
σ_d^2	0.000043614		The variance of the difference between the means
σ_d	6.60E-03		Standard deviation
t-test result	**30.08**		Results are *Very Significant*

Appendix C

Hypothesis t-test calculations

Table C3. T-test for hypothesis 3

Parameters	Chem. absorption with Mineral Sequestration Methods 1, 2 and 5	All other CO_2 recovery with Mineral Sequestration	Remarks
$\sum x$	-0.212	-0.241	Total sum of all values
N	3	17	No. of values
x mean	-0.071	-0.014	Total value/N
$\sum x^2$	0.015	0.034	Sum of all x^2
$(\sum x)^2$	0.045	0.058	Square of ($\sum x$)
$\sum d^2$	2.19E-04	3.04E-02	$\sum d^2 = \sum x^2 - [(\sum x)^2 / N]$
σ^2	1.09E-04	1.90E-03	$\sigma^2 = \sum d^2 / (N-1)$
σ_d^2	1.48E-04		The variance of the difference between the means
σ_d	1.20E-02		Standard deviation
t-test result	**2.42**		Results are *Rather Insignificant*

Appendix D

Error Analysis using Additive Formulae

Eqn 1 from **APPENDIX B** is re-written as:

$$GWP^{(\text{Vertical Injection})} = (\mathbf{A}*1) + (\mathbf{B}*2) + (\mathbf{C}*25) + (\mathbf{D}*320) \ldots\ldots\ldots \textit{Eqn.(2)}$$

Where $\mathbf{A} = \sum CO_{2\ldots}$; $\mathbf{B} = \sum CO_{\ldots}$; $\mathbf{C} = \sum CH_{4\ldots}$; $\mathbf{D} = \sum N_2O\ldots$
(Total sum of emissions due to energy requirements)

And their respective total errors are expressed as Δa, Δb, Δc and Δd

Then the error **R** for $GWP^{(\text{Vertical Injection})}$ can be calculated as:

$$\mathbf{R^2} = (\Delta a * 1)^2 + (\Delta b * 2)^2 + (\Delta c * 25)^2 + (\Delta d * 320)^2$$

An error of 10% is estimated for the LCI data (Table 4.2 again):

$\Rightarrow$ Δa = $11.14 + 3.71 + 3.33 + 9.5 - 85.5 = \underline{-57.82}$

$\Rightarrow$ Δb = $\underline{0.00403}$

$\Rightarrow$ Δc = $\underline{0.0139}$

$\Rightarrow$ Δd = $\underline{0.0000673}$

By inserting the new LCI values into *Eqn.(2)*: R^2 = 3343.27

$\Rightarrow$ **R** = **57.82** (10.06% error)